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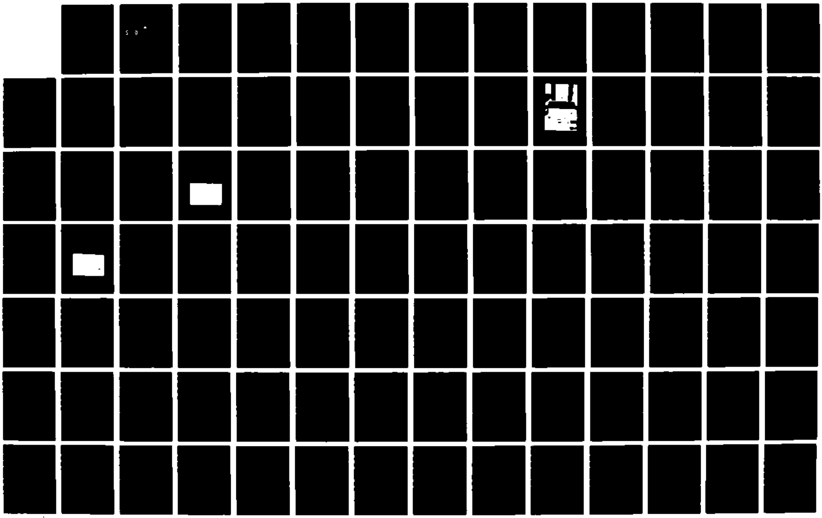

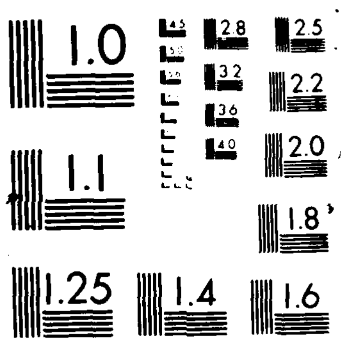
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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

COMPOSITE RELIABILITY ENHANCEMENT
VIA PRELOADING

by

David Keith Bell

June 1987

Thesis Advisor: Professor Edward M. Wu

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Many Navy applications of composites, including ships' superstructures, submarine air flasks and missile rocket motor casings, require high strength and reliable materials. Composite strength reliability is dictated by individual fiber breaks at low loads (lower tail) and the accumulation of the fiber failure sites.

This study examined the effects of applying a preload to a graphite/epoxy composite tow prior to complete polymerization of the matrix. The objective was to break the (inevitable) weak fibers and minimize the effects of the associated stress concentrations, subsequently limiting the clustering of the fiber failures. By eliminating the lower tail, the shape of the Weibull distribution is reduced, thereby enhanceing composite reliability.

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Composite Reliability Enhancement Via Preloading

by

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Lieutenant, United States Navy
B.S.M.E., University of Kansas, 1979

Submitted in partial fulfillment of the
requirement for the degree of

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ABSTRACT

Many Navy applications of *composites*, including ships' superstructures, submarine air flasks and missile rocket motor casings, require high strength and reliable materials. Composite strength reliability is dictated by individual fiber breaks at low loads (lower tail) and the accumulation of the fiber failure sites.

This study examined the effects of applying a preload to a graphite/epoxy composite tow prior to complete polymerization of the matrix. The objective was to break the (inevitable) weak fibers and minimize the effects of the associated stress concentrations, subsequently limiting the clustering of fiber failures. By eliminating the lower tail, the shape of the Weibull distribution is reduced, thereby enhancing composite reliability.

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I. INTRODUCTION

In the 1960s, *Composite Materials* were referred to as "Space Age Materials". Today, composite structures are common through out our society. The rapid growth of the composite materials industry has been phenomenal, perhaps only exceeded by the advancements in computer technology. The concept of composite materials is simple, in that two or more structurally compatible materials are combined to produce an end product with attributes greater than the sum of the constitutes. But as new applications for composite materials are developed so follows an increase in unanswered questions with regards to reliability, especially associated with vital national defense systems, public transportation systems and aerospace and hydrospace exploration. As engineers it is important that we do not let the state of the art exceed the state of the science. We must have answers to those difficult questions concerning composite material applicability, maintainability and reliability.

Composite reliability is the focus of attention at the Advanced Composites Laboratory at the Naval Postgraduate School, Monterey California. Here questions are being investigated regarding composite reliability as a function of service life, strength and test methodology. The primary goal of composite material research is to be able to have a better understanding of how composite materials behave over an extended service life and to further investigate the mechanics of composite strengthening. A secondary function is the investigation into improved testing methods so that research techniques can be translated into production applications.

The primary *objective* of this study was to investigate composite reliability as a function of the strengthening mechanisms. This was accomplished by studying the affects of preloading a graphite bundle prior to complete curing of the epoxy matrix. After the matrix had cured, the graphite strand ultimate tensile strength was determined and the results were compared to a benchmark value based on previous testing.

In addition, individual fiber testing was conducted so that a mathematical model may be developed in order to determine the optimum bundle preload level. Fiber testing was also conducted in order to demonstrate that the Integrated Fiber Testing system developed at the Naval Postgraduate School (NPSIT) could be use as a viable and accurate test method. This was accomplished by conducting fiber testing using an INSTRON Model 4200 materials tester using current American Society of Testing and Materials (ASTM) procedures and comparing the results obtained using the NPSIT system. Graphite fibers having different strength properties were tested in order to show that the testing systems used could accurately ascertain any small differences in composite properties. The focus of this study was on fiber diameter and fiber tensile strength.

II. BACKGROUND

Load bearing graphite composite materials consist of high strength / high modulus graphite impregnated with a ductile reinforcing matrix. The performance characteristics of the composite material are controlled by three factors:

- Strength and modulus of the graphite fiber
- Strength and modulus of the epoxy matrix
- Effectiveness of the bond between the matrix and fiber, with regards to the mechanics of load transfer at the interface.

The overall tensile failure process of this simple system is extremely complex, however for the purpose of this study this can be simplified by assuming a two dimensional model and that failure initiation occurs within the fiber only. This failure model was first presented by B.W. Rosen (Ref.1 and 2). It consisted of parallel fibers in a homogeneous matrix, loaded in tension, assuming a uniform strain supported primarily by the fibers.

The most important concepts developed in this classical study were the fact that the fibers were considered to have statistically distributed flaws or imperfections. Theses flaws resulted in fiber failure at various stress levels, therefore Rosen considered each fiber as a series of links and that the individual fiber failure process was a function of the weakest link principle. Finally, that the statistical strength distribution of theses flaws could be approximated by a Weibull distribution.

A. FIBER FAILURE PROCESS

Initially when a fiber *bundle* ,without epoxy, is loaded in tension, the individual fiber failures occur randomly at the site of a flaw at a load much less than failure load ($x_1 < x_f$). When this occurs the stress (σ_1) in the fiber becomes zero, and the stress in the surviving fibers increase to a new stress level equal to some value $K * \sigma_1$. The existence of some individual fiber failures may not be catastrophic in that the increase in stress is shared equally by the remaining fibers as long as $K * \sigma_1 < \sigma_f$. Then applied tension x can be increased to a new value $x_2 > x_1$ then this process is repeated until $K_i * \sigma_i \geq \sigma_f$. Excluding any effects due to twist or friction, catostophic bundle failure occurs after each individual fiber breaks once.

When the fiber bundle is impregnated with an binder matrix the mechanical behavior of the composite *strand* is altered. The addition of the matrix creates a unique load transferring system. This provides for transverse load sharing between each individual fiber and longitudinal load sharing to another segment of the fiber. The matrix also provides the mechanism for localizing the effects of microcracks within the composite material. These two functions combined provide for the distinct mechanical performance of fiber reinforce composite materials.

The composite failure process based on Rosen's failure model, with matrix binder, predicts different results from dry bundles. When the initial load x_i is applied initial fiber failures still occur at the inevitable flaw sites, however the effects are confined to a localized region. Stress σ decreases to zero, and the shear τ in the matrix reaches a maximum value. The axial load is transmitted by this shear to only the neighboring fiber segments, (see

Figure 1). The neighboring fibers now show a *load concentration* due to the fiber break. At the broken fiber tip there exists a length of fiber which is ineffective in carrying the applied load. This is known as the *ineffective length* δ. The increase in shared stress on the immediate neighbors is substantially greater then that shared by the fibers that are a greater distance from the failure site.

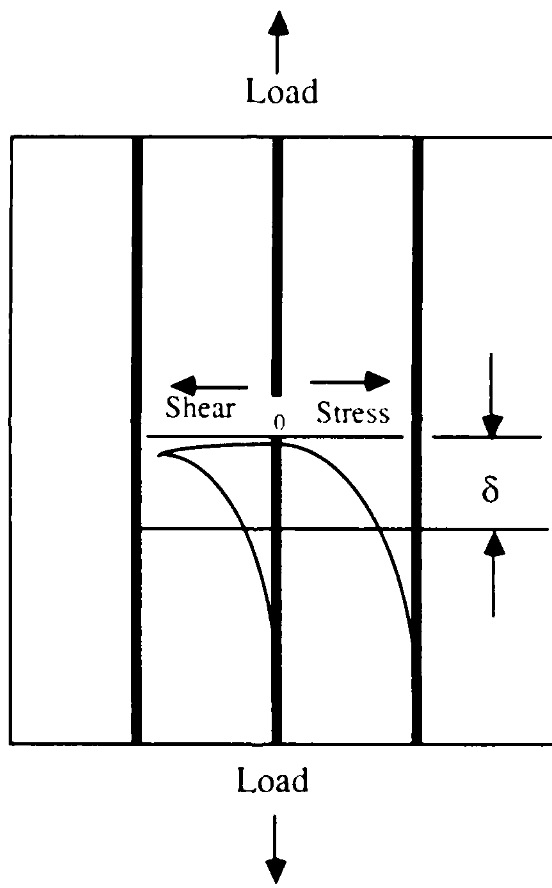

Figure 1. Fiber Bundle Model

The determination of the ineffective length δ is difficult, and requires an understanding of the shear stress distribution along the interface. The ineffective length is estimated by Rosen [Ref. 1] to be:

$$\delta = 1/2 \ \{(V_f^{-1/2} - 1) E_f/G_m\}^{1/2} \ \cosh^{-1}\{[1 + (1 + \varphi)^2] / 2[1 - \varphi]\} \ d_f$$

V_f - Volume fraction of fiber

E_f - Modulus of fiber

G_f - Shear modulus of matrix

φ - Fiber efficiency or the fraction of the undistributed stress value below which the fiber is considered to be ineffective

d_f - Fiber diameter

B. COMPOSITE FAILURE

In general there are three basic modes of composite failure. The first is debonding which is failure at the fiber/matrix interface which is caused by a high interface shear stress (Figure 2a). This failure may start with a single broken fiber and propagates within the interface, along the fiber length, which in turn drastically increases the ineffective length δ. Thus increasing the likelyhood of the crack propagating to another flaw site. The study of this type of failure identifies the need for improving the interface properties such as adhesion and toughness properties of the epoxy (Note: $x_i << x_f$). The second type of composite failure is crack propagation (Figure 2b). This occurs when an initial crack is developed at the flaw site and propagates transversely across the composite. Crack propagation is controlled by the fracture toughness of the matrix and fiber and thus minimizing the effects on local load sharing. This failure mode may be associated with some slight debonding. (Note: $x_i << x_f$).

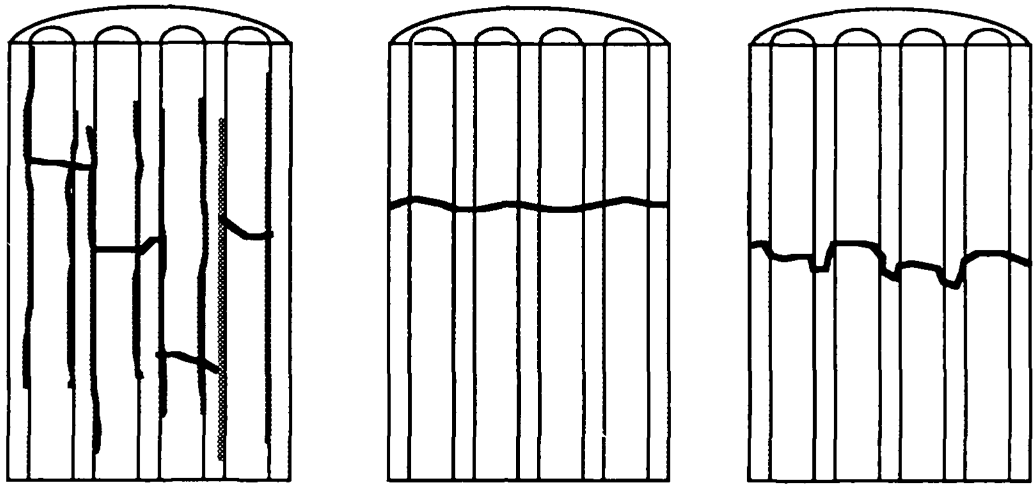

Figure 2a. Figure 2b. Figure 2c.

Figure 2. Composite Failure Model

Finally, if debonding and crack propagation are controlled then composite failure occurs when as load is increased, the number of statistically distributed fiber failures accumulates in the vicinity of one cross section such that when the load shared in the surviving fibers exceeds the ultimate load of the system ($x_i \geq x_f$). This mode of failure is usually a combination of debonding and crack propagation, occurring at a much higher load level, (Figure 2c).

C. LOAD SHARING

The most pronounced effects of adding a matrix binder to the fiber bundle is that of load sharing. This is best discussed using a microbundle model developed by S.L. Phoenix. [Ref. 3]. This model, (Figure 3) is made up of **n** fibers, each consisting of **m** links having a length of δ, the ineffective length. In each microbundle (= **n** $* \delta$) there exists a set of statistically distributed flaws. When the load x is applied the fibers will sequentially fail, in accordance with a Weibull distribution function.

$$F(x) = 1 - \exp[-(x/\beta_X)^{\alpha}]$$

Where α is the shape parameter and β is the scale parameter.

Because the individual fiber consists of **m** links , the weakest link theorem applies. Therefore, the value of β_X is a function of gage length and must be corrected for GL.

$$\beta_{2X} = \beta_{1X} \ (GL_1 / GL_2)^{1/\alpha}$$

When an initial fiber failure x_1 occurs in a *weakest* link the load on each immediate neighbor increases to a value $X=K_1*x$, where K_1 is the load concentration factor and $K_1>1$, (Figure 3). If another weak link exists within the region of concentrated load, then a second fiber failure will prematurely occur. This in turn creates an additional load sharing burden on the neighboring fibers $X = K_2*x$, where $K_2>K_1>1$, (Figure 3). Therefore, randomly created load concentrations may prematurely break a larger number of fibers at a load x_l than would otherwise normally occur, subsequently weakening the composite. J.M. Hedgepeth [Ref. 4] provided quantitative values to the load concentration factors, where $K_1 = 1.33$, $K_2 = 1.60$, $K_3 = 1.83$ and $K_4 = 2.03$. Meaning, for example, that the load in the fibers adjacent to three consecutive fiber breaks equals 1.83 * applied load .

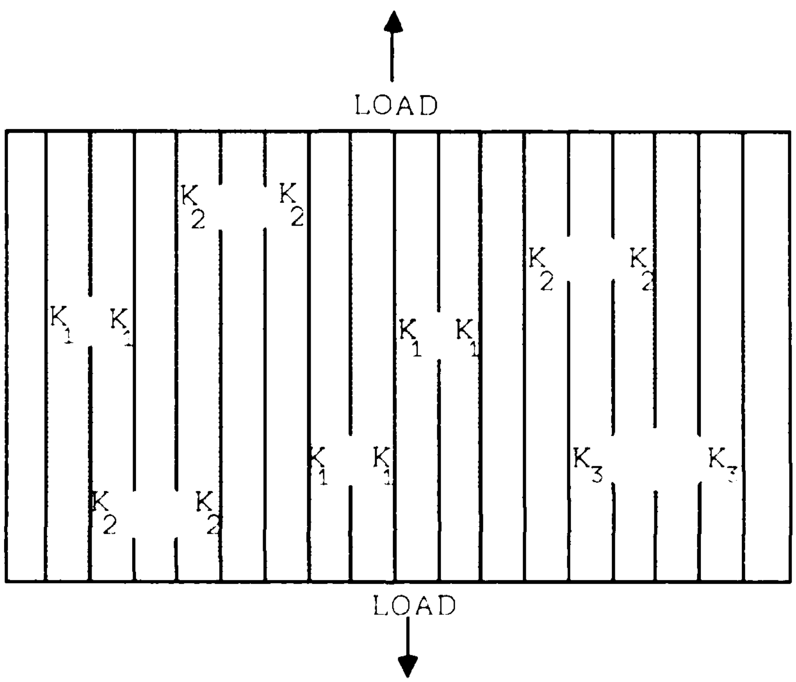

Figure 3. Load Concentrations Model

If the random fiber breaks occuring at x_i were dispersed throughout the composite the effects of load concentrations K would be minimal, however this can not be controlled. Therefore an attempt must be made to control the effects of the spatial clustering of fiber breaks and load concentrations in a local region.

A.S. Tetelman [Ref. 5] and C. Zweben [Ref. 6] provide excellent summaries of the composite failure process and the effects of load concentrations. Tetelman also discussed a few concepts for minimizing load concentrations and controlling crack propagation. These include the use of discontinuous fibers, using fibers or matrix consisting of various modulus of elasticity and the use of prestressing at elevated temperatures In fact prestressing composite bundles at elevated temperatures was proven to be a viable solution during experimental work conducted by E.M. Wu. [Ref. 7]. G.J. Mills [Ref. 8] has also studied the effects of prestressing Boron/Epoxy prepregs by rolling.

D. COMPOSITE RELIABILITY

The reliability of a composite structure depends on a definite characterization of the weak strength distribution (the *weak* lower tail). Definitive evaluation of the lower tail requires a large sample size and consistent material production system.

Such a data base for composite material performance is usually developed from either limited fiber/bundle testing or complete system testing of a small sample size. A small data base, when combined with the existence of the statistically distributed flaws or imperfections in the graphite fiber due to manufacturing, processing or handling practices, makes the behavior of a given composite structure difficult to predict. When a multimillion dollar rocket motor casing or aircraft component consists of an enormous number of fiber *links*, performance reliability becomes dependent upon a statistical study of the strength characteristics. Because of the existence of the fiber flaws, the strength values of the Weibull distribution are well dispersed within the lower tail. This imposes great restrictions on the allowable design limits for the composite structure. Ideally, there would exist nearly no dispersion in the test data (coefficient of variance approaches zero) and then the data would be completely reliable for a given strength level.

This study will focus on improving composite strength reliability by the use of preloading the fiber bundle prior to the curing of the epoxy resin in order to remove the weak fiber sites (lower tail of the Weibull distribution) and decrease the dispersion of the composite strength.

III. EXPERIMENTATION

The experimental work was concentrated in two areas. First, determining the diameter and strength of the individual fiber and second, determining the strength characteristics of a graphite tow subsequent to preloading.

The material tested was from a Hercules Magnamite high strength graphite, type AS-4 spools 008 and 019. The graphite bundle consisted of 3000 fibers with a nominal diameter of 7 micrometers and a denier of .005746 grams/inch.

A. FIBER TESTING

Individual fiber testing was a vital part of this study which provided the essential data required to determine the appropriate preload. First the fiber diameter was determined then the fiber failure strength. This information was used to develop a Weibull probability plot to statistically determine the number of fiber failures as a function of applied load.

To study the feasibility of using an alternative testing method, two testing methods were used during this study. The first method was the use of an Instron Material Tester (INSTRON), (Figure 4), with associated ASTM procedures to determine fiber failure load. Second, using a Integrated Testing system under development at the Naval Postgraduate School, Monterey, California. (NPSIT), (Figure 5).

Figure 4. INSTRON Testing System

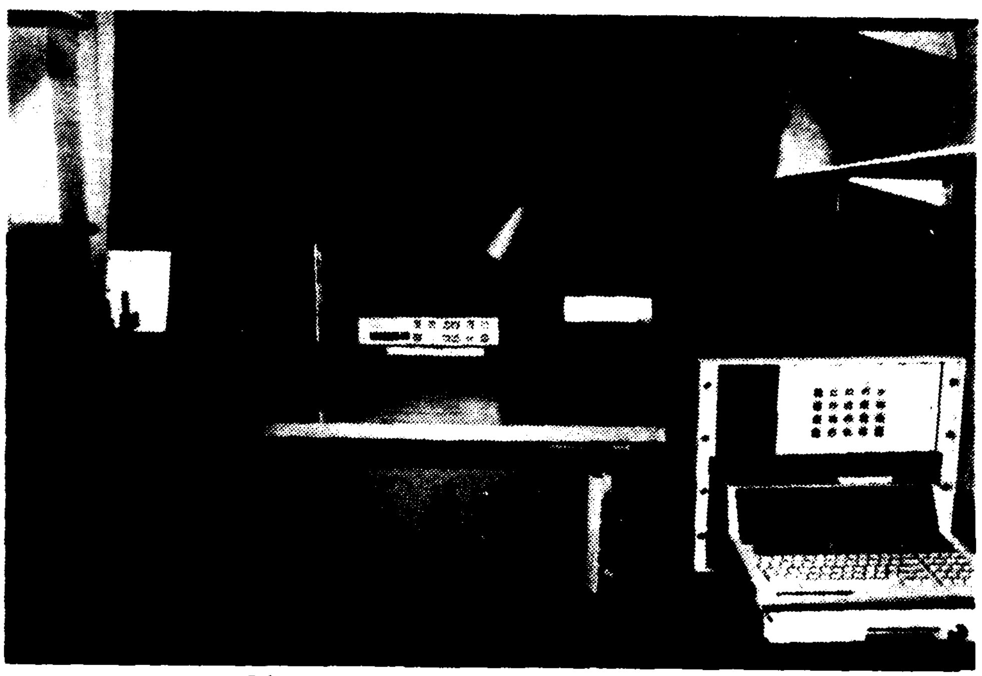

Figure 5. NPSIT Testing System

The primary advantage to the NPSIT system is that the fiber diameter as well as the failure load can be readily determined on the same test stand. This minimizes the handling of the test samples and bias the statistical parameters.

The correlation between fiber test length and failure load has been well established in past studies and is not addressed here. A gage length of 5 centimeters was used for fiber testing. Strain rate or crosshead speed also has an effect on test results, however this effect was not studied. A constant speed of 10 percent of gage length per minute (in accordance with ASTM procedure) was employed.

Regardless of the testing method used, sample preparation (Appendix A.) and testing parameters were identical.

1. Fiber Diameter

Current methods for determining fiber diameter, as outlined in ASTM procedures, call for the use of the Scanning Electron Microscope (SEM). This is a time consuming and some what arduous task when testing large numbers of fibers.

Recent work at the Naval Postgraduate School, Monterey, has provided two additional methods which are more conducive to this study. The principles and procedures as developed by T. A. Bennett [Ref. 9] are based on the physical optics, that if a illuminated beam of light is directed at the fiber that a diffracted light pattern is produced which is perpendicular to the fiber (Figure 6).

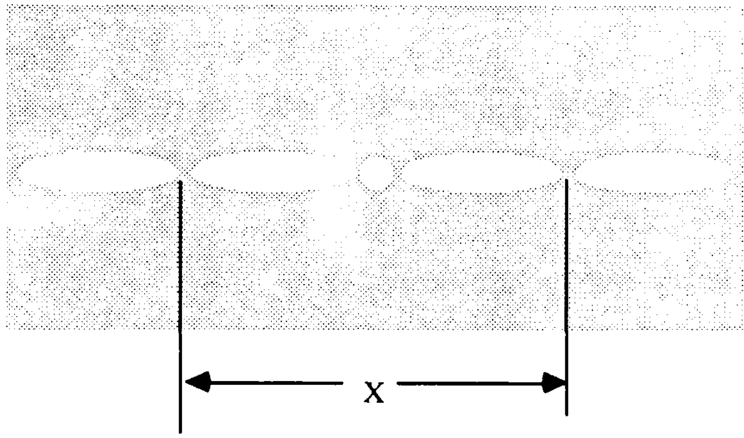

Figure 6. Diffraction Pattern

The first method Bennett looked at was the use of a photoconductive cell to measure the distance between nodes (null intensity in the diffracted light pattern). The second method consists of the use of a microneye interfaced with an Apple Plus II microcomputer. Bennett [Ref. 9] and M. Storch [Ref. 10] then developed the data acquisition techniques necessary to accurately determine fiber diameter. The required test configuration is essentially the same for both methods, however, since only the photocells was used in this study , only those associated procedures will be further discussed.

The test equipment (Figure 5) consists of ; a low power (.052 mW) Helium-Neon laser, which provides the required light source of known wave length (lambda = 632.8EE-09 meters). A focusing lens, a spatial filter and a collimating lens are enclosed as one unit and mounted on the end of the laser. This is necessary in order to produce the parallel light pattern. The fiber is mounted on the test stand which by use of micrometers allows for longitudinal and transverse adjustments, rotation of the sample and adaptability to the load testing device. At the end of the tracks are two photocells mounted to adjustable pedestals which allow for transverse adjustments. The photocells are connected to two Fluke 8840A multimeters.

2. <u>INSTRON Load Test</u>

Individual fiber load testing was performed using the Instron Load Tester Model 4206 (INSTRON) inconjunction with compatible data acquisition systems. The data acquisition system to be used during this study is the Hewlett-Packard 3497A Data Acquisition/Control Unit and the Hewlett-Packard HP-85 for computer programming. Appendix B provides a detailed listing of the Interactive Data Acquisition Software (IDAS). IDAS was design to minimize operator effort and ensure accurate and reproducible test results. All IDAS procedures were written in accordance with American Society of Testing and Materials (ASTM) St^ndard Specifications.

After the required program is loaded enter RUN and then follow the outlined steps in Appendix B. The programs use the function keys to provide for flexible data acquisition. Options are normally provided for a CRT/printer output or with the graphics plotter.

Fiber diameter was measured prior to this test with the use of the NPSIT test system.

The IDAS software includes the following programs.

LDCALB - Load Cell Calibration: Characterization of the strength of a fiber required absolute calibration of the load transducer. This was accomplished by calibrating the digital output of the load transducer by standard weights at six levels. This provided absolute calibration all analogue and the analogue to digit interface.

MCTST - Characterization of the stiffness of a fiber requied the calibration of the system compliance. The total compliance measured (C_t) is the sum of the fiber compliance (C_f) plus the system compliance (C_s), all three are a function of applied load level P.

$$C_t(p) = C_f(p) + C_s(p)$$

The system compliance C_s is comprised of the compliance of the testing machine, of the cardboard tab and the adhesiv. hich bonds the fiber to the tab. If the system compliance is assumed to be constant, then a single calibration constant (effective gauge length of zero) is determined as recommended by ASTM procedure D-3379-75(82), (Ref. 11). as discussed in ASTM procedure 3379-75(82), the effective gauge length can be extrapolated from measurement of the total compliance using three different gauge lengths. The short coming of this procedure is that it assumes that system compliance is independent of load level P. The latter was observed to be a gross assumption. Compliance calibration was accomplished using an actual zero gage length sample. In this case, the fiber compliance C_f term vanishes and the total compliance measured is the system compliance. Furthermore, the compliance, over the entire load range of the strength of the fiber measured was recorded and the data fitted by a second degree polynomial. This second order polynomial was then used to calibrate the tensile strength test data, thereby compensating for the non-linear depencey on the load level.

QFIT - Quadratic Curve Fit: This program reads the saved Machine Compliance data and provides the three coefficients of a quadratic curve. These values E, F, G were then recorded for further use in the fiber test program to mathematically subtract from the total displacement the displacement associated with the system compliance.

FTST - Fiber Test: Is the primary program in this series. INPUTS, allows for the input of all key parameters necessary to determine the actual fiber ultimate strength. The test is run for 30 seconds at a speed of .1x gauge length (5 millimeters/minute on a 50 millimeter sample). The A, B, C, E and F inputs as discussed above are required to perform the necessary mathematical calculations. AQUIR, provides for the actual proof test and data acquisition. Once the sample is ready the program will adjust for the initial tension then start the timer, providing for 300 data readings during the 30 second. run. The results can be displayed on the CRT/printer using GRAF or on the HP Plotter using PLOT. SAV-DAT and RD-DAT provide for the storage and reading of test data. CAL, mathematically subtracts system compliance from the total displacement and provides the unbaised results.

LDTST - Load Test: Provides for a quick check of the load cell calibration using the original A, B and excitation voltage from the LDCALB results.

LDSTOR - Load/Store: is a data management tool for transfering files.

3. NPSIT Load Testing System

The Naval Postgraduate School Integrated Load testing system was developed as an alternative testing method which provides for the determination of fiber diameter as well as failure load with one test system.

The data acquisition and software is essentially the same as that used with the INSTRON test system. The only exception being that a short program was added to FTST so that fiber diameter and failure load are recorded on the same file for easier access.

By following the procedures in Appendix A and Appendix B, the NPSIT system can be quickly initialized and ready for fiber testing. After the FTST program is loaded, mount the fiber sample in the clamps. First measure the fiber diameter, as discussed and then enter AQUIR. The distinct difference between this test method and the INSTRON test method is that the NPSIT drive motor is manually controlled by the operator upon prompt from the HP-85 program, where as the INSTRON tester is software controlled.

All fiber data is recorded, displayed and stored in the same manner as with the INSTRON test.

B. TOW TESTING

The objective of graphite tow testing was to determine the the effects on the strength characteristics as a result of applying a preload. Experimentally, AS-4-019 graphite bundles, from the same spool used in fiber testing, were tested.

1. Initial Set-up

The samples were prepared by paying the graphite out on a table and applying a 2 kilogram load. Then copper tabs (1 inch x 1.5 inch) were fasten to the bundle at a gage lengths of 10 inches using an epoxy mix as the adhesive. The 2 kilogram load removes the slack and aligns the individual fibers within the bundle. The copper tabs provide for an area for the bundle to be gripped in the Instron tester.

The Instron Universal Testing Instrument Model 4206 was used to provide the tensile load to the test samples. This system was used in conjunction with the 4200 Series Expanded Control Console with data acquisition being provided by the use of an IBM PC-AT. The Instron/IBM data acquisition on system provides for the real time graphical display of load versus displacement and the creation of a data base for additional computations and graphical outputs. The initial operator and report files are established prior to the commencement of testing to generate the desired reports and graphs.

2. Preloading Bundles

Prior to applying a preload, the Graphite bundle was impregnated with the epoxy matrix. The matrix consisted of a mixture of Dow DER-332 resin (55 percent by weight) and Texaco Jeffamine T403 (45 percent by weight). (Note: extreme care and good work practices must be used when handling the epoxy products). After thoroughly mixing, the epoxy was placed in a vacuum chamber to remove the entrapped air. The graphite bundle was then dipped into epoxy and allowed to soak a sufficient amount of time to allow for complete impregnation. The bundle is removed from the epoxy bath and the excess epoxy is removed.

The impregnated strand was removed and placed on the oven curing rack, Figure 7, and air cured for 19 hours. The strands were then placed in the Instron grips. Preload was calculated, from the fiber statistical parameters in order to break a desired segement of the lower tail weaker fibers, for a preset displacement of 2.5 millimeters. at a rate of 5 millimeter/minute and immediatley unloaded. The samples were placed in a temperature controlled oven and cured for 16 hours at 60 degree centigrade.

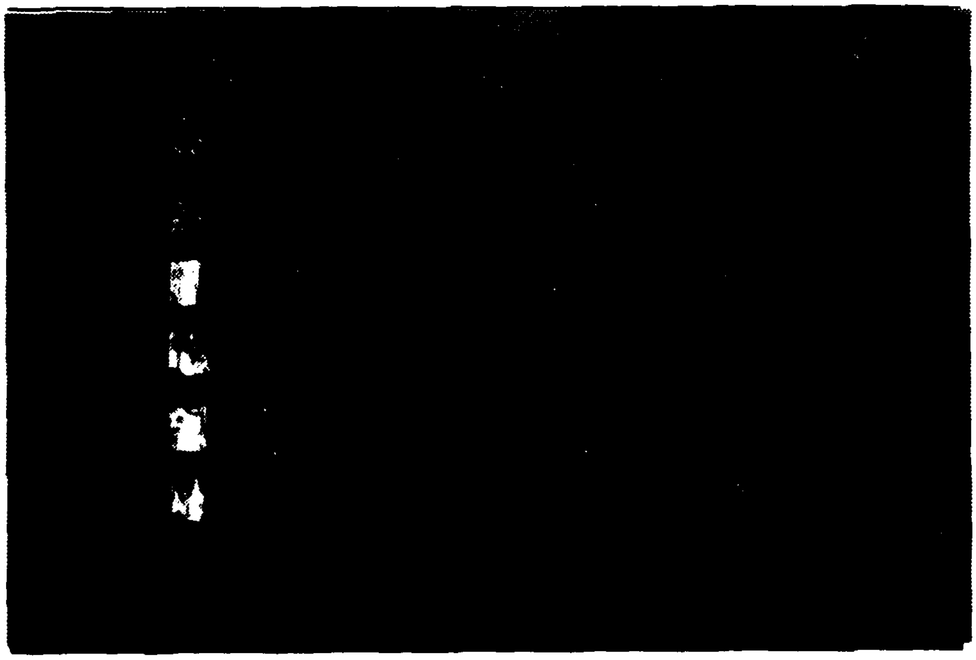

Figure 7. Oven Curing Rack

The final resin content of the strand was determined by weighing a few random samples and comparing to the weight of the dry bundle.

$$\%_R = \frac{W_T - W_B}{W_T}$$

Where W_T is the total weight of the strand and W_B is the weight of the bundle (denier x gage length). A resin content of 55 to 60 percent is desired.

3. Load Testing

The failure load of the final product (the matrix impregenated composite strand) was determined using the Instron/IBM system described earlier. After the strand is mounted in the test grips the desired test files are inputted and the machine crosshead speed is set a 10 centimeters per minute. The test is allowed to continued until complete tensile failure of the composite strand occurs. The final output provides for the maximum load in kilograms and displacement at failure in millimeters. A graphical report may also be generated.

VI. RESULTS

A. FIBER TESTING

1. Fiber Diameter

A review of the statistical summary of the fiber diameter results (Table I), provides a clear indication that the test method used for determining fiber diameter produced consistent and accurate results. The normal probability plot, Figure 8, shows how the AS-4-008 series and the AS-4-019 series graphite diameters compared to the *merged* results.

A total of 79 samples were measured from the AS-4-008 graphite spool, with a mean diameter of 7.233 microns versus 82 fiber samples from the AS-4-019 spool with a mean diameter of 7.245 microns. The large variability of fiber diameter (as measured by the magnitude of the standard deviation) verifies that the fiber diameter is not consistent over the entire length.

Exploratory effort was expended in the adjustment of the test stand, optimizing the distance between the fiber and the projected plane (the photocell).. This was required to compensate for the narrow width of the photocell window. It was necessary to adjust the test stand so the width of the node was nearly as wide as the photocell. If the node is too wide, there exists several locations of maximum resistance readings. If the the node is too narrow, too much light saturates the photocell, thus making it impossible to locate the center of the node.

TABLE I: STATISTICAL SUMMARY OF SINGLE FIBER TESTING

	N	Shape α	Scale β	Mean	Std Dev	Coef. Var.
008 Series Load (gmf)						
Merged	68	4.28	15.79	14.40	3.56	.28
Instron	34	3.62	15.80	14.26	4.20	.33
NPSIT	34	5.75	15.72	14.56	2.78	.21
Diameter(μm)	79			7.233	.233	
019 Series Load (gmf)						
Merged	69	3.94	15.45	13.99	4.11	.30
Instron	35	3.32	15.52	13.91	4.82	.36
NPSIT	34	4.86	15.33	14.06	3.20	.24
Diameter(μm)	82			7.245	.301	

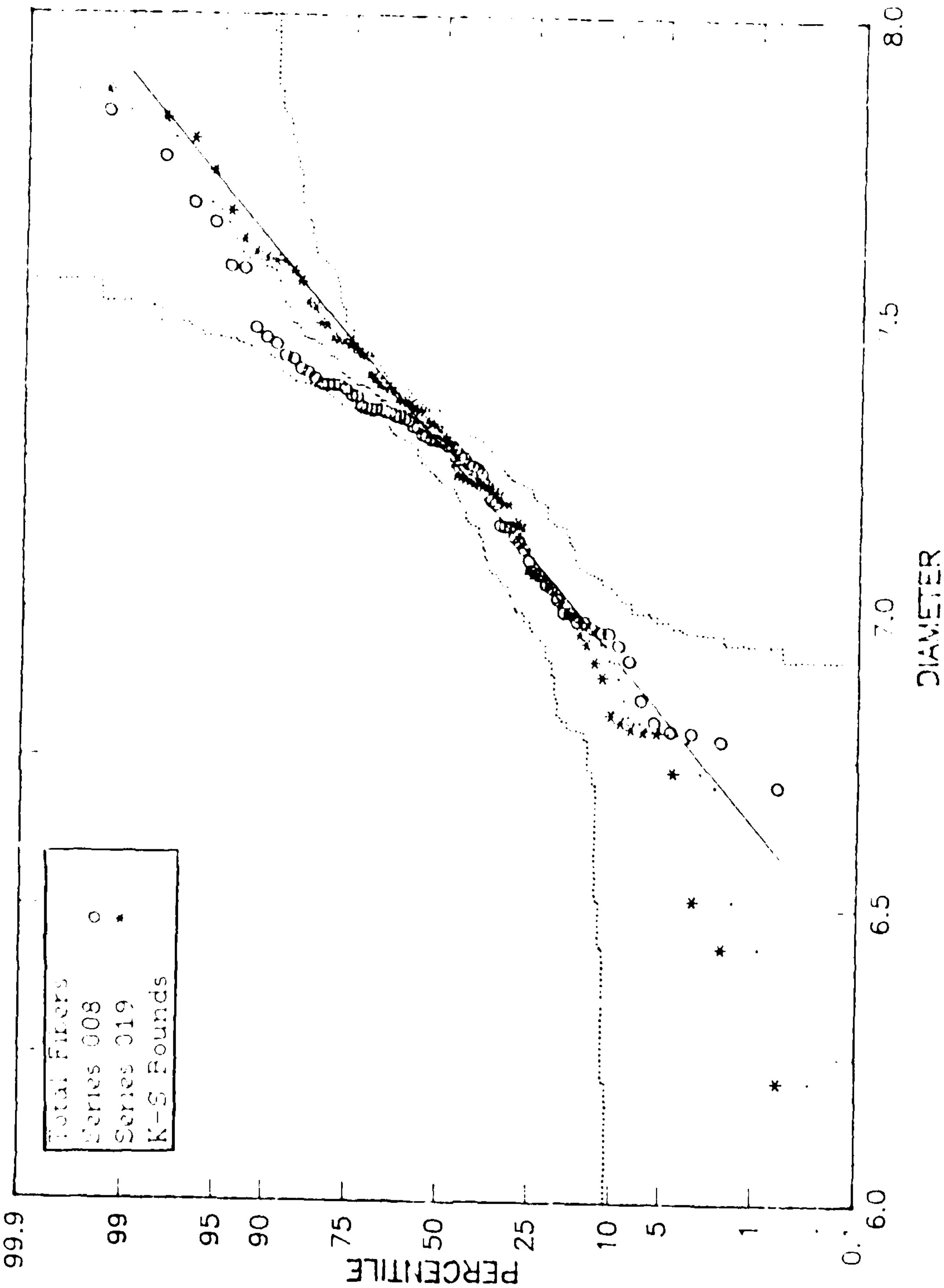

Figure 8. Normal Distribution Plot of Fiber Diameter

2. <u>Fiber Failure Load</u>

Interpretation of fiber failure data is focused on two areas

-- Comparison of test results from INSTRON and NPSIT testing to identify any differences.

-- Comparison of the statistical strength for samples from two different spools.

In Table II statistical parameters from Table I are employed for comparison of the INSTRON and NPSIT test methods.(see Figures 9 and 10).

TABLE II. FIBER LOAD RESULTS

	Mean(gmf)		Std Dev	
	008	019	008	019
INSTRON	14.26	13.91	4.20	4.82
NPSIT	14.56	14.06	2.78	3.20
Difference	+2%	+1%	-15%	-15%

Comparing the first two columns of TABLE II, it is apparent that the mean strengths of the samples measured with the NPSIT are, slightly but consistently, higher for both spools tested. Comparing the last two columns, the variabilities of the measured samples in the NPSIT are, significantly and consistently, lower for both spools. These observation substantiate the hypotheses that the NPSIT, which integrates the fiber diameter measurement with the strength measurement, enables the elimination of several handling and storage steps, thereby minimizing the associated accidental damage.

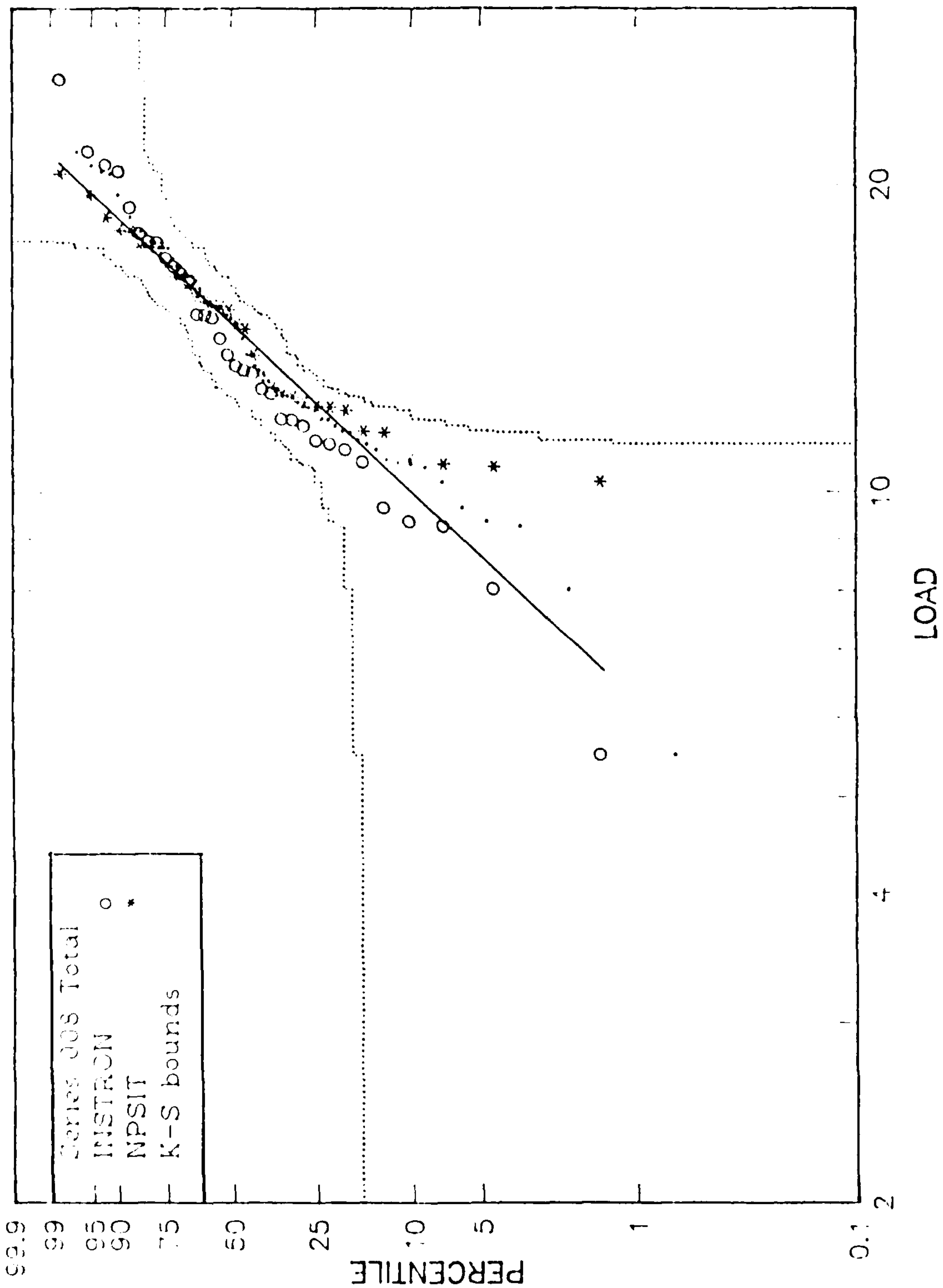

Figure 9. Weibull Distribution Plot of Fiber Load

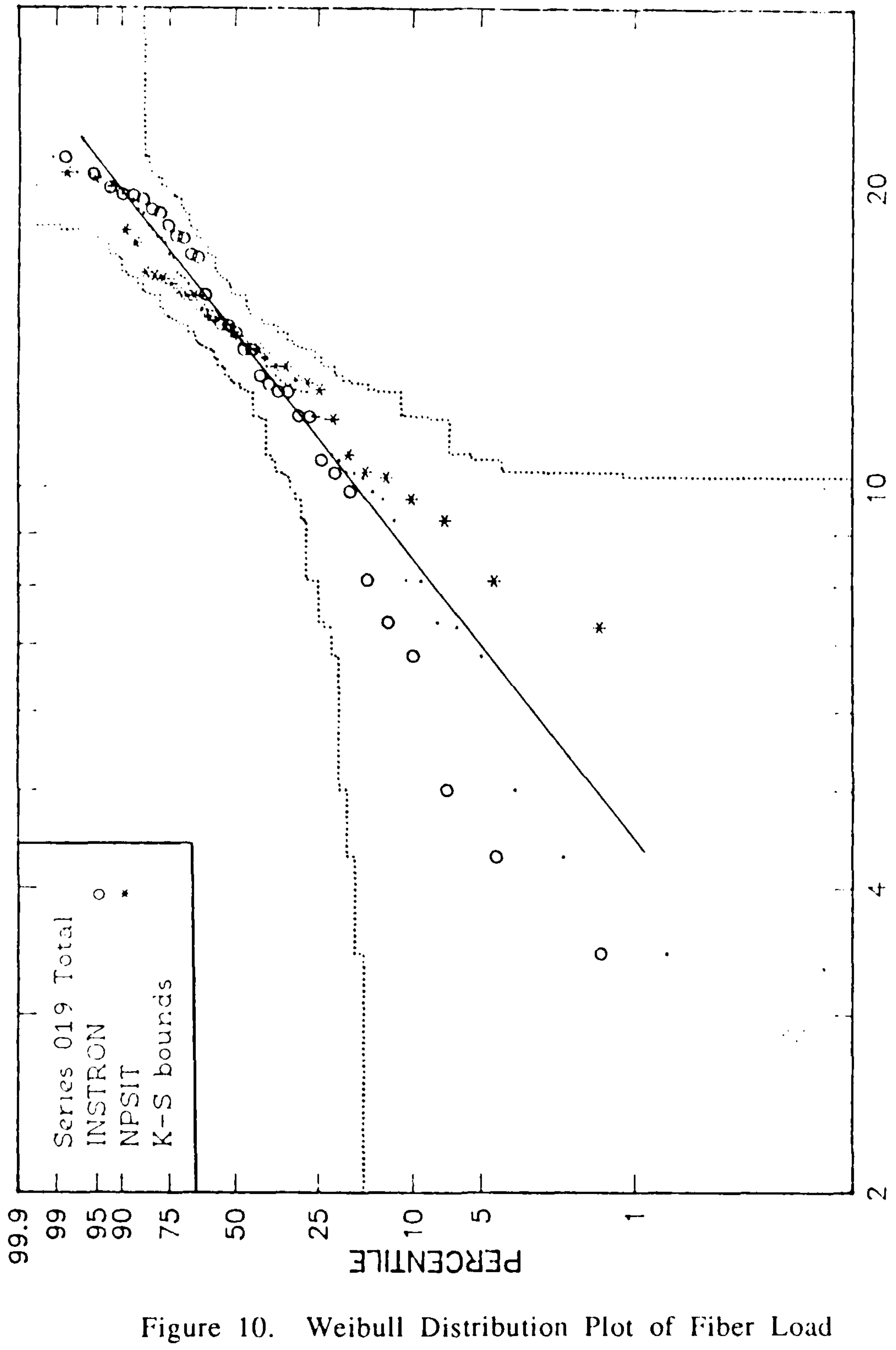

Figure 10. Weibull Distribution Plot of Fiber Load

Minimization of this damage results in a shift of the lower tail, of the Weibull plot, to the left (evident in both Figure 9 and Figure 10 for samples labeled *) and a significant reduction of variability and the standard deviation. Minimization of the handling damage cannot increase the instrinsic strength, therefore has no effect on the upper tail (again evident in Figures 9 and 10). The shift of the lower tail changes the geometric centroid, of the probability distribution function (pdf), therefore causing a slight increase of the mean. The consistency between the quantitative measurement with the qualitative expectations support the conclusion that the integrated NPSIT test is a worth while improvement.

For comparison of the statistical strength of the two spools, the strength is modeled by the two parameter Weibull distribution, Table III. The parameters, as based on Maximum Likelihood Estimation, of the respective data sets are summarized:

TABLE III. FIBER LOAD WEIBULL PARAMETERS

	Alpha α			Beta β		
	NPSIT	INSTRON	MERGE	NPSIT	INSTRON	MERGE
008	5.75	3.62	4.28	15.72	15.80	15.79
019	4.86	3.32	3.94	15.33	15.52	15.45
Diff	-18%	-9%	-8.5%	-2.5%	-1.8%	-2.2%

Again, note the significant difference between the α parameter (which is inversely associated with variability) for the two spools. This is particularly evident when handling has been reduced On the other hand, consistent with the above discussion, the difference between the β parameter (associated with mean strength) is slight. Physically, composite samples fabricated with the 019 spool which has a smaller α (or larger variability) will have a larger number of fiber breaks than those fabricated with the 008 spool. In accordance with the local load sharing model, the larger number of fiber breaks will increase the stochastic process of clustering of failure sites hence, leading to a higher composite scatter. Therefore, preloading spool 019 and observed accompanied change of composite variability will offer both a verification of the load sharing model and explore the practicality of improving composite reliability.

Complete tabulated results for all fiber diameter and tensile strength measurements are found in Appendix D.

B. TOW BUNDLE PRELOAD

The objective of preloading the tow bundle, prior to matrix binder impregnation was to decrease the variability of the composite strength. It was established in [Ref.1] and [Ref. 2] that composite failure occurred sequentially when weak fiber failure began at low load levels. As applied load is increased, the number of broken sites increased and formed spatially clustered failure sites leading to stress concentrations, the most severe of which causes catastrophic failure. This failure process can be observed by comparing the load deformation curve of a matrix-free tow bundle (curve B in Figure 11) and a matrix impregnated bundle, the composite (curve C).

For the tow bundle curve B, the initial slope of the load deformation curve is the sum of all the filaments in the bundle. As the deformation

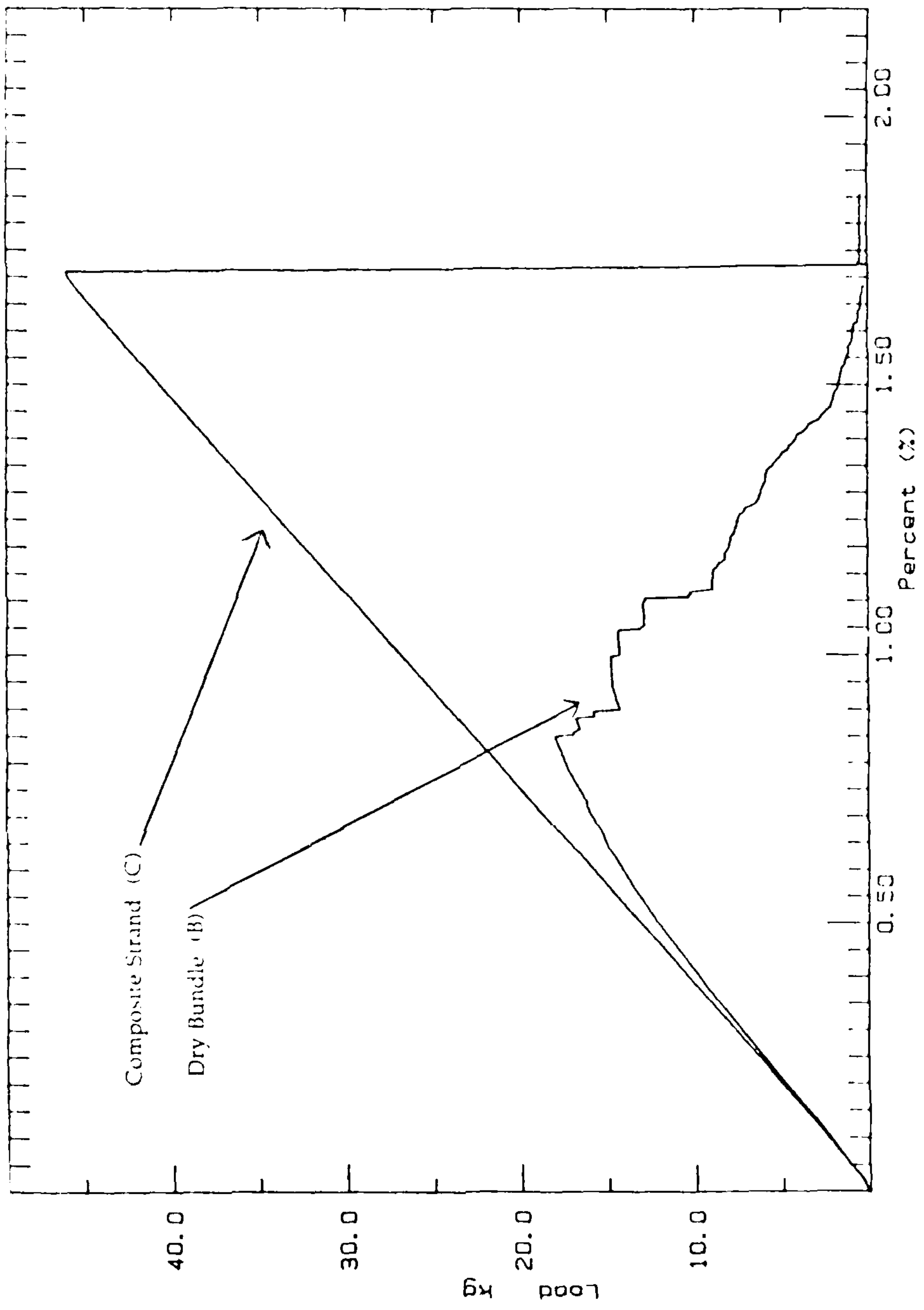

Figure 11. Composite Deformation Curve

displacement is increased, the weakest fibers break and the load carrying capability of the entire bundle is lost, thus resulting in a decrease in slope such that the secant modulus is equal to the sum of modulus of the surviving fibers. This continues until only a few very strong fiber survive and the secant of the load deformation curve of the bundle approaches horizontal.

For the composite curve C, the initial slope of the load deformation curve is the same as that of the bundle curve B, since both have the same number of filaments. Within the composite, weak fibers start to fail at 0.3 percent strain as in the bundle. However, in the presence of the matrix binder, the load carried by the broken fiber is transferred to the neighboring fibers via the matrix and, instead of the entire fiber, only a portion equal to the ineffective length is lost. The ineffective length is approximately equal to 10 fiber diameters or in the case of graphite, in the order of 100um. Such a minute loss can not be detected from the resolution of the load deformation curve. As result the load-deformation curve remains apparently linear up to the point of catastrophic rupture even though numerous filament failures sites accumulated internally.

Therefore, it is desirable to develop a preload procedure to break the inevitable weak fibers, without creating stress concentrations which lead to premature undue breakage of the neighboring fibers. This is possible if the preload can be performed before the matrix can effectively transfer the load. Subsequently when the matrix becomes effective, the load around the broken site can be transferred to the neighbor without causing spatial clustering of broken fiber sites and subsequently reducing the variability of the ultimate strength.

The most obvious implementation is to perform the preload on a dry bundle prior to the introduction of the matrix binder. Exploration proved that this approach was not practical. In the absence of matrix binder, a broken filament unleashed the stored elastic energy dynamically leading to fraying and lost of alignment of the filaments, (see Figure 12). In fact this phenomenon occurred when preload was applied to a bundle wetted in a matrix but prior to polymerization. In such a case the surface tension of the uncured polymeric matrix is insufficient to contain the dynamic energy release of the breaking filaments. Therefore, the impregnated bundle was allowed to air cure prior to preloading to ensure sufficient surface tension to prevent fraying.

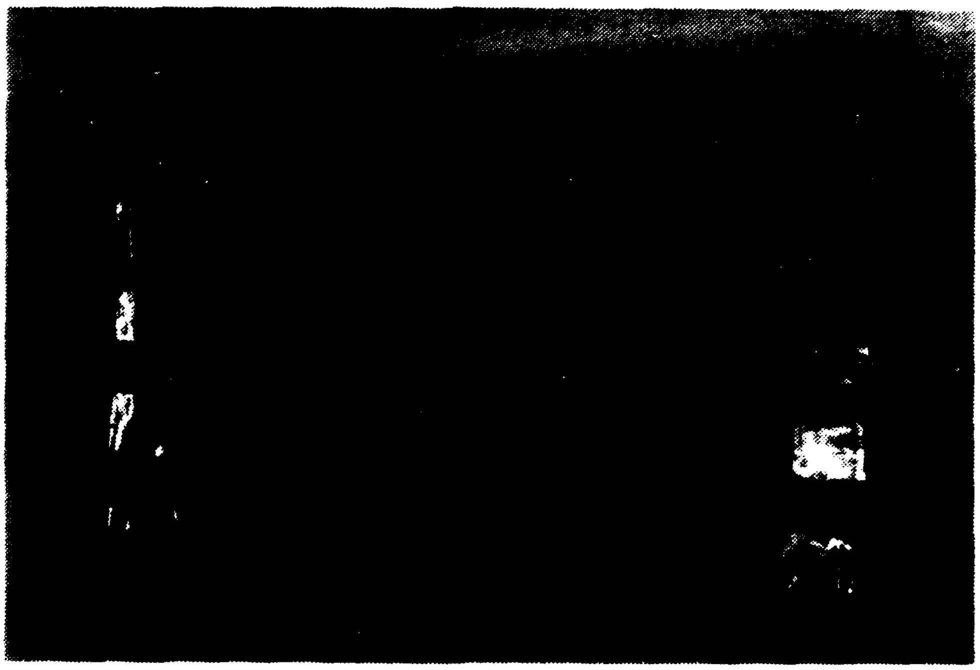

Figure 12. Fraying of Preloaded Strands

Based on the results from Appendix C, the preload level at a deformation of 3.0 millimeters would break 40 percent of the fibers. It can be expected that this is the effective strain level desired to verify the preload mechanism. Because of the fraying problem associated with this method, the preload level was reduced to a level below which fraying occurred. After a series of samples were tested at various strains, it was determined that 2.25 millimeters provided the best results for a range of room temperature curing times of 19 to 22 hours. At 2.25 millimeters, it can be predicted that 13 percent of the fibers were deliberately broken.

1. Procedure

The finalized preload procedure consisted of :

- Homogeneous mixing of epoxy and curing agent
- Impregnate graphite tow with epoxy in a flat pan
- Partially cure epoxy matrix at room temperature for 19 hours
- Preload samples, under displacement control to 2.25mm (.9% strain)
- Final cure samples at 60°C for 16 hours
- Tensile test samples at crosshead displacement of 10 mm/min.

Ultimate tensile test results for the preloaded and non-preloaded samples are listed in Appendix D. Table XV.

2. Interpretation

The tensile strengths associated with the preloaded sample are compared with the bench mark non-preloaded samples. The non-preloaded samples were prepared essentially by the same procedures listed above with the exception of air curing and preloading, using an automated filament winding set-up with no manual handling. The expected quality of the non-preloaded samples is comparable to well controlled production quality. The preloaded samples were prepared individually with all manual handling. The quality was expected to be lower than a fully developed production process. One can expect that any improvement observed with the preloaded sample may be realized in a fully developed process.

The tensile strengths of both the non-preloaded and the preloaded samples exhibited statistical scatter precluding a deterministic comparison. Comparisons are made first at the non-parametric level and then at the parametric level together with consequences in structural efficiency and reliability.

a. Non-Parametric Comparison

Distribution-free properties of the two sets of data are presented for an objective comparisons. However, because of sample size (<25) is not sufficiently large, conclusions should be considered as qualitatively valid.

The histograms of tensile strength for the non-preloaded and the preload sample are presented in Figure 13. Preloading process is seen to have no influence on the central tendency of the strength data but has a preceptable affect of removing the lower *weak* tail. The reduction of the lower tail is beneficial to both the structural efficiency and the structural reliability. Several relevant distribution-free properties are listed in Table IV.

TABLE IV. COMPOSITE STRENGTH PROPERTIES

	Mean	Std Dev	Medium	Mode	Skewness
No Preload	46.942	3.07	47.220	47.776	-.27
Preload	46.418	2.12	46.420	46.424	-.003
Change	-1%	-31%	-2%	-2%	~100%

Consistent with the visual comparison, column one suggests no significant change of the mean strength between the two processes. However column five indicates that the nonpreload strength skewed to the weak tail whereas the skew is drastically reduced after preloading. This was also consistent with visual identification of lower tail shift after preloading, see Figures 13 and 14.

b. Parametric Comparison

The local load sharing model, [Ref. 3] provides the theoretical bases for the Weibull model for the non-preloaded samples. Characterization of the non-preloaded strength data by a two parameter Weibull model is therefore proper. Similar justification for the preload sample is not yet firmly established; this data can also be fitted by a two parameter Weibull model for expediency for comparison, with the understanding that the procedure is *ad hoc*. The Weibull parameters obtained through maximum likelihood estimator for the two sets of data are tabulated in Table V.

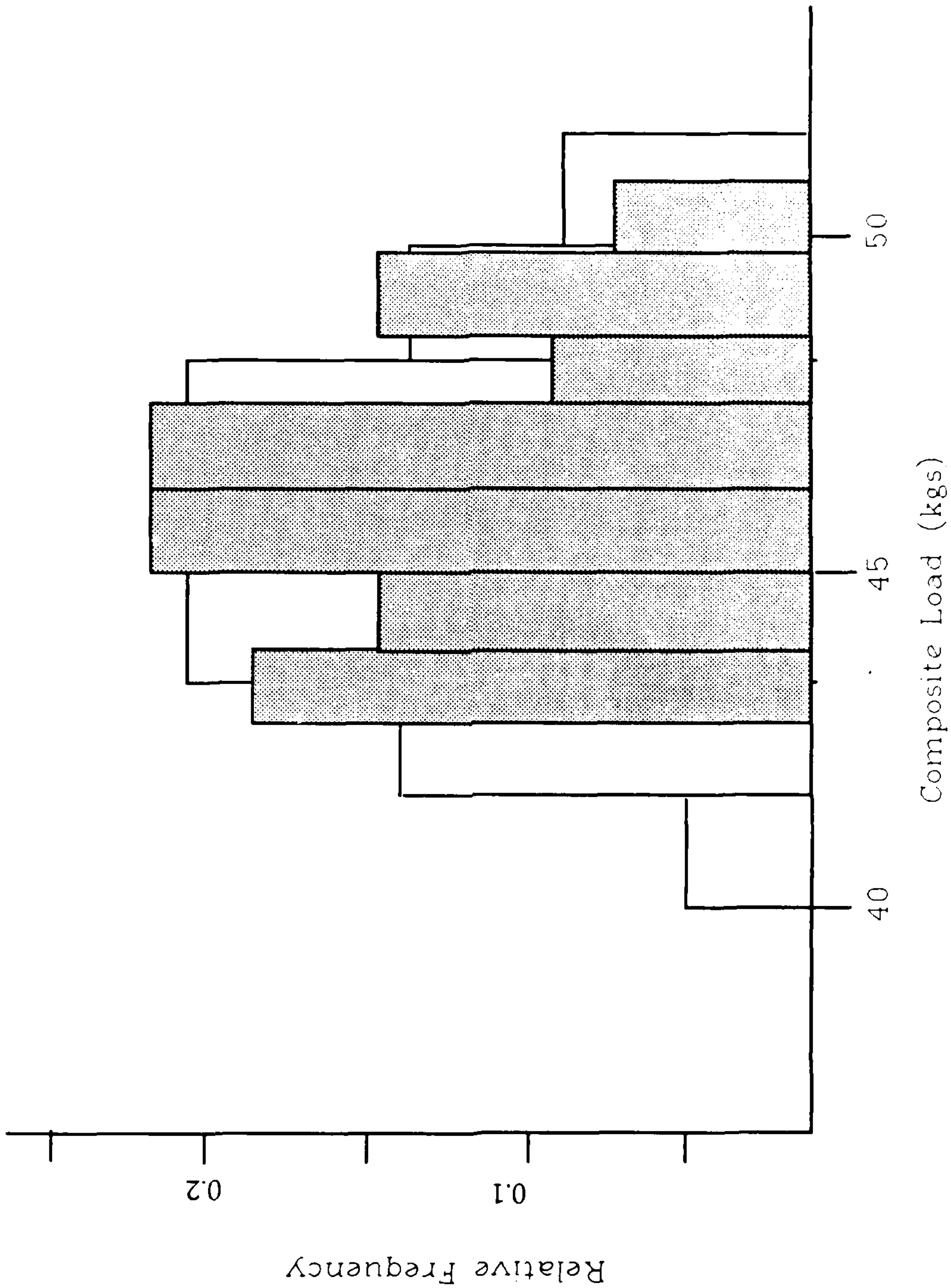

Figure 13. Histogram of Composite Failure Load Results

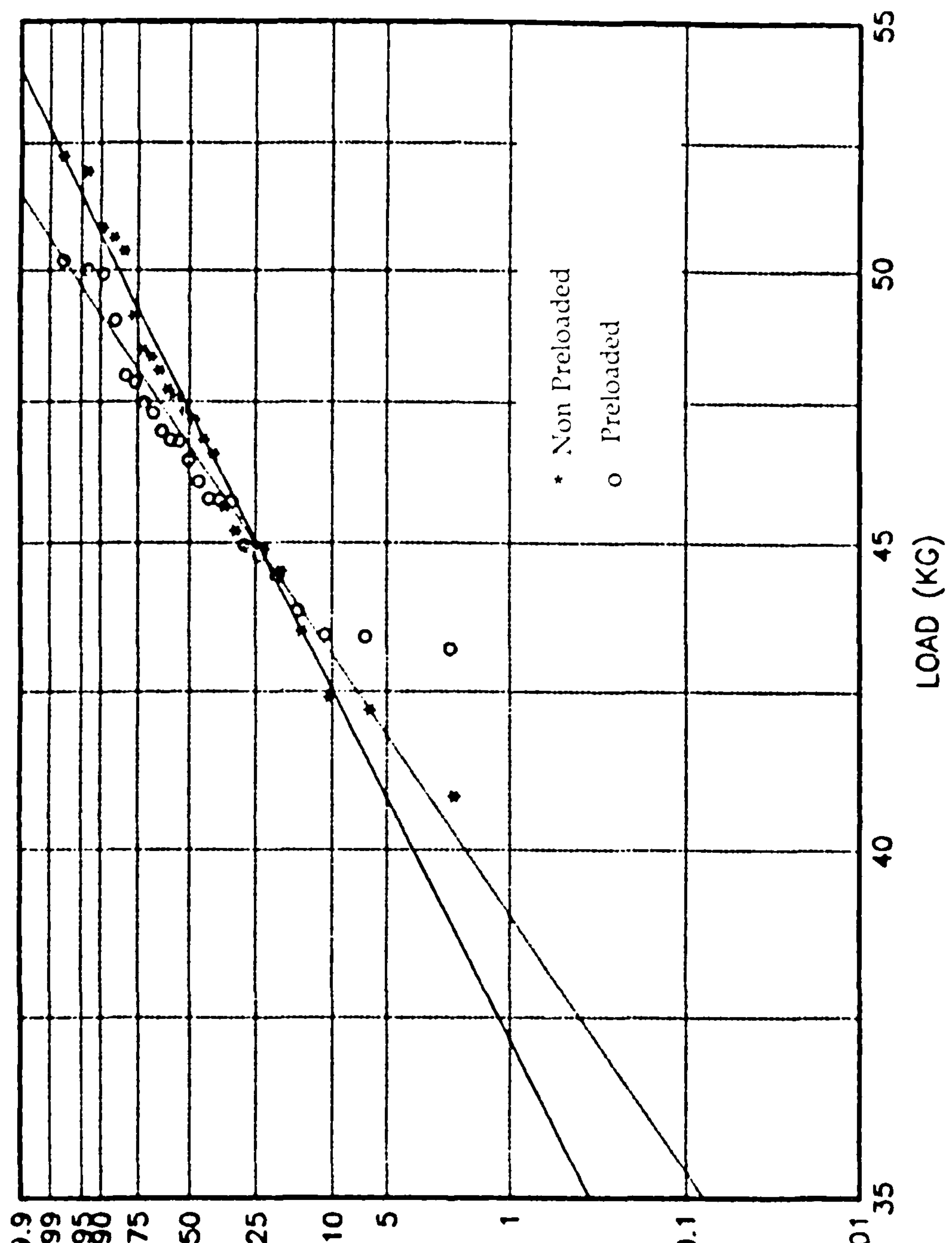

Figure 14. Weibull Distribution Plot of Composite Failure Load

TABLE V. COMPOSITE WEIBULL PARAMETERS

	shape	Scale
Nopreload	17.48	48.34
Preload	23.45	47.43
Change	+34%	-2%

The Weibull representations are also consistent with the non-parametric observations, namely no significant central tendency shift as reflected to almost identical β values; but a significant decrease in scatter as reflected in the increase in α. The increase in α affects structural efficiency (at a given reliability level). The magnitude of the potential improvement is illustrated in Table VI.

TABLE VI. SUMMARY OF RELIABILITY AS A FUNCTION OF APPLIED LOAD (KGS)

Reliability	Nonpreload	Preloaded	Change
$1x10^{-3}$	32.56	35.33	8.5 %
$1x10^{-5}$	25.02	29.03	16%
$1x10^{-6}$	21.93	26.31	20%

For composite applications where functional reliability of $1x10^{-3}$ is required, structural efficiency goes up by 8.5 %. For applications where national security reliability is $1x10^{-5}$, structural efficiency goes up by

16%. For composite applications where man-safe reliability (1×10^{-6}) is required, structural reliability goes up by a significant 20%.

Alternately, an increase in α can be interpreted as to cause an increased reliability at a given design stress level, (defined as a fraction of the mean strength). For example, The probability of failure (F) at 80% of the mean decreases from 1.2% for the nonpreloaded composite to .32% for a preloaded composite, a delta of 75%

Finally, it was pointed out, earlier, that modeling the preloaded data by the two parameter Weibull model was *ad hoc*. In fact, the preloaded data when presented alone suggest a bimodel trend (Figure 15). Fitting a shape parameter , α to the lower tail return a value of $\alpha = 270$. This large value of α effectively provides for a structure that would be practically 100 % reliable at any load level below the transition between the modes (approximately 43 kilograms) or, a 100% increase in strength at 1×10^{-6} reliability. Thus potentially, the improvement from preloading is even greater. However, it must be understood that the number of samples tested herein is insufficient to establish a bimodel system. This latter interpretation is subject to confirmation by more extensive exploration.

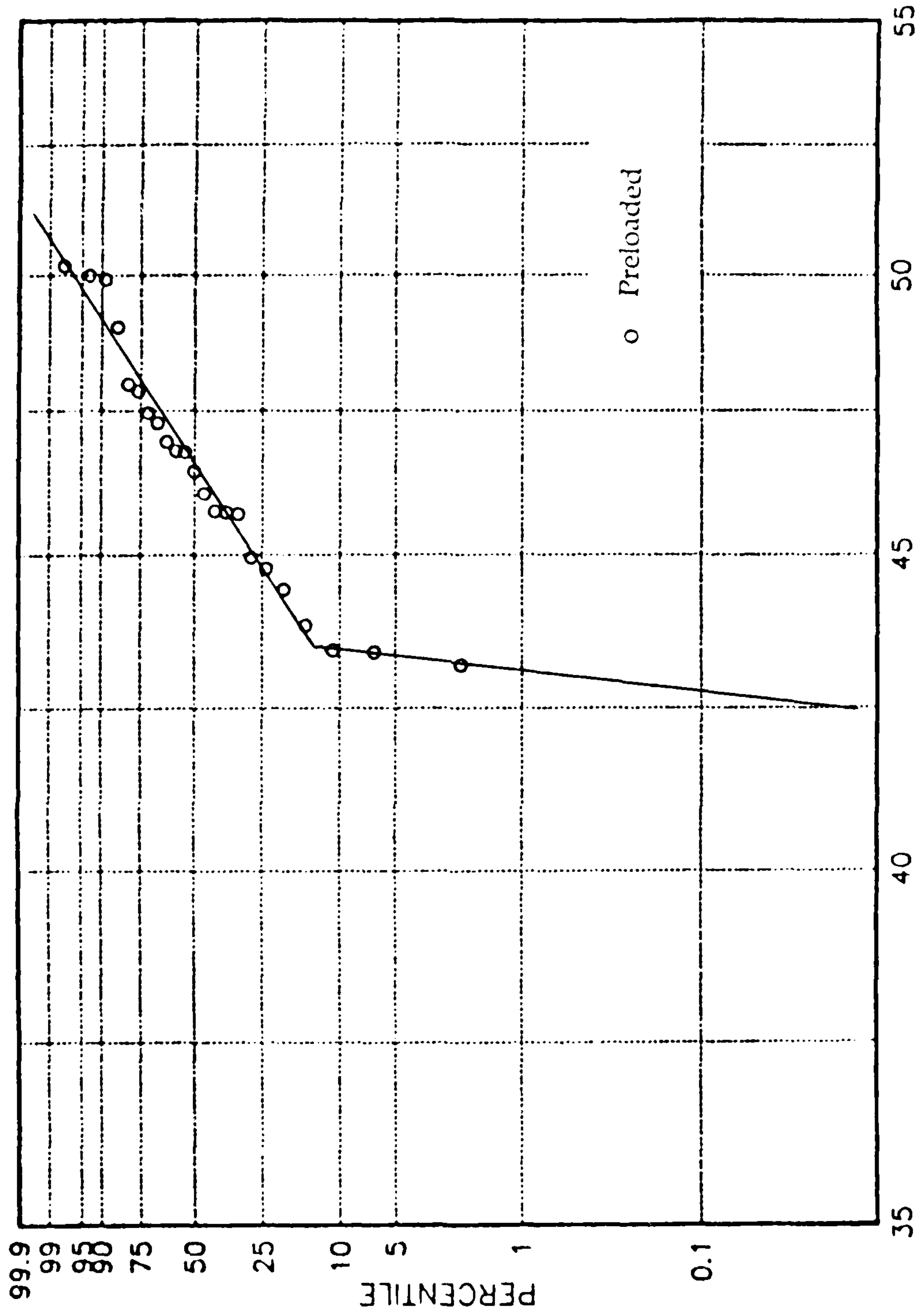

Figure 15. BiModel Trend

V. CONCLUSIONS AND RECOMMENDATIONS

As a result of individual fiber testing it can be concluded that Individual fiber Test system developed at the Naval Postgraduate School, NPSIT, is a viable testing method which produces accurate and reproducible results. The NPSIT test, is a one step test system which provides for the determination of fiber diameter and ultimate failure load. This test method minimizes the handling of the sample, thus providing a truer characterization of the fiber. An additional advantage is that the test was performed in 40 percent less time as compared to using the INSTRON tester in conjunction with the Scanning Electron Microscope.

This study clearly demonstrated that preloading a composite, prior to complete polymerization, has a profound effect on the lower tail of the Weibull distribution, hence the overall reliability of the composite. In addition, the optimum preload level can be independently mathematically estimated, based on fiber tests results.

Further studies are recommended in the areas of;

- Use of the Micron Eye in determining fiber diameter.
- Alternate composite gripping methods.
- The effects of preloading as a function of strain rate, air curing time and different strains.
- Preloading composite strands at elevated temperatures.
- Statistical modeling to account for a multi-model distribution resulting from preload.

APPENDIX A. SINGLE FIBER TEST PROCEDURES

1. FIBER SAMPLE PREPARATION

The individual fibers were mounted on cardboard forms for ease of storage and handling. The samples were prepared in accordance with ASTM procedure D-3379-75 (reapproved 1982) [Ref 11.].

- Fabricated cardboard mounts. (3" X 5/8").
- Remove 10 inch strand of graphite form roll.
- Using a magnifier, carefully separate strand to expose individual fibers.
- Pick up one end of fiber with adhesive tape and cut to approximately twice the desired length.
- Lay fiber over cardboard mount and center (Figure 16).
- Affix the ends of the fiber with tape.
- Place cardboard on storage rack and label.
- Apply Duco cement at the ends of the fiber.

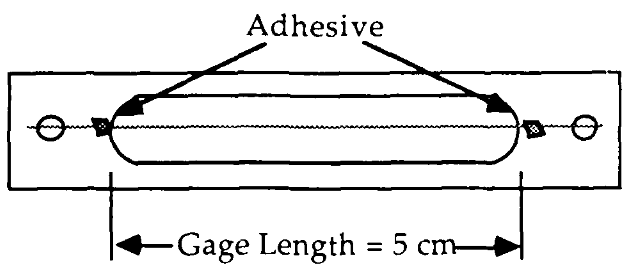

Figure 16. Fiber Mount

2. CALIBRATION OF FIBER DIAMETER SYSTEM

Before the fiber diameter can be determined using the diffracted laser beam associated with the Naval Postgraduate School Integrated Test, NPSIT a calibration curve must be established .

The calibration curve used to determine the fiber diameter shows the results when comparing the fiber diameter as measured using the diffracted laser beam (NPSIT) compared to the diameter recorded when using the Scanning Electron Microscope (SEM). Six test specimens were mounted on a 15 centimeter cardboard mount and then samples from each end were removed and carefully marked. These samples were then put under the Scanning Electron Microscope (SEM) and several diameter readings were recorded and averaged. The Scanning Electron Microscope results were used as a standard for determining the fiber diameter.

Figure 17 is a graphical representation of the calibration result, with the equation of the straight line being.

$$\text{Diam} = .89 * (\text{NPSIT}) + .3614 \qquad (1)$$

A linear curve fit proves most useful and the results for an exponential or polynomial curve fit are essentially the same.

It should be noted that as the fiber diameter increases, the difference between the NPSIT results and the corresponding SEM results also increases. By reviewing Figure 6, this can be predicted because as the fiber diameter increases the spacing between the nodes (X) decreases, and so does the width of the associated dark areas. Therefore it becomes much more difficult (and less accurate) to find the center of the low intensity node using the photocells.

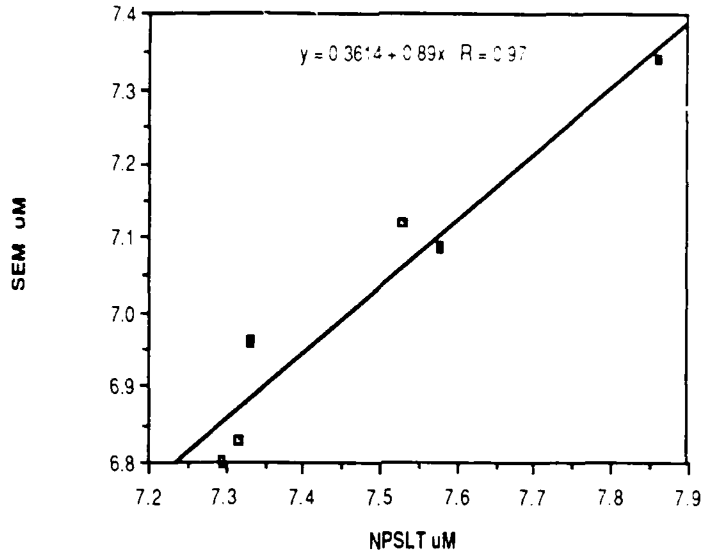

Figure 17. Diameter Calibration Curve

3. FIBER DIAMETER MEASUREMENT PROCEDURES

The fiber sample is first mounted in the test by inserting between the upper and lower clamps Then the entire stand is adjusted longitudinally to achieve the desire distance (L) from the photocells. (note: the spread of the light pattern increases as L increase). The photocell pedestals are then adjusted to an approximate position corresponding to the predicted distance between the nodes, (ensure there is sufficient travel in the micrometers to allow for left and right movement) . After the pedestals are secured in place measure the distance between the photocells and record as C. Mount the micrometer in place on the photocell pedestals and zero the reading. Now the final distance between the photocells can be easily determined by adding C to the micrometer reading Delta C.

The final steps for determining the fiber diameter are performed with the lab lights off, therefore complete familiarization of all test equipment adjustments is mandatory. After the laser is turned on and the shutter opened, a red light (beam) will appear (avoid looking directly into the laser beam). It may be necessary to manually adjust the laser position and the transverse position of the test stand to obtain the optimum diffraction pattern at the point of interest on the fiber. Then manually adjust the height of the photocells to align the light pattern to the center of the photocells. The preliminary adjustments are now complete.

To determine the distance between the second nodes, each photocell pedestal is adjusted using the micrometers. The final adjustments are made transversely to locate the position associated with the highest resistance reading on the multimeter. Readjust both pedestal separately several times to ensure maximum accuracy. After you secure the laser power, record the digital micrometer reading as Delta C.

Calculate the fiber diameter, a, from equations (2) and (3) of [Ref 9.].

$$X = C + \text{Delta } C, \qquad (2)$$

$$a = n\,(\text{lambda})\ L \ / \ (X/2), \qquad (3)$$

n = corresponding node (eg $n = 2$),

$L = 598.6$ mm. $C = 115$ mm.

The accuracy of the fiber diameter is dependent upon the operators techniques, so five or six readings should be recorded and averaged.

4. L0AD TESTING

Fiber failure load was determined using either the Instron Universal Testing Instrument Model 4206 (INSTRON) or the NPSIT system. A Sensotec Inc. 50 gram Load Cell Model 31/1435-01 was used to sense fiber load. The Machine Complaince test, a cross head speed of .1 millimeters per minute was best and for the Fiber Test a speed of 5 millimeters per minute (.1 x gage length) was used.

INSTRON testing is a semi-automatic process when used in conjunction with the HP - 85 computer and an HP 3497A data acquisition system and the Interactive Data Acquisition software outlined in Appendix B.

NPSIT testing also used the same data acquisition system , however manual operation of the drive motor is required. The Control Technics Corp. Linear Actuator Model CTC-160 (gear head ratio 262:1) and associated Micrometer Controller Model MMC-10 provide the same functions as the Instron cross head. The Speed Enter was set at -200 on the thumb wheel to achieve 5 mm/min and the Ratio Enter was set at 40 for a total travel of 45 turns in one minute.

After load cell calibration and system compliance tests are complete, Fiber testing was conducted as follows.

- Run FTST program.
- Carefully mount sample in clamps.
- Select DIAM (NPSIT only).
- Measure Fiber Diameter (NPSIT only).
- Select INPUTS and input initialize data.

- Select ACQUIR, then carefully cut the cardboard mount near the bottom.
- Remove slack in fiber (NPSIT only)
- Hit program CONT and controller R/S simultaneously
- After fiber breaks and data acquisition stops, stop motor controller.
- Graph and store data.

With the INSTRON test system fiber diameter was determine from the NPSIT first. Also this system has automatic fiber slack removal functions.

APPENDIX B. INTERACTIVE DATA ACQUISITION SOFTWARE

The Interactive Data Acquisition Software (IDAS) was designed for use with the HP-85 microcomputer and the HP-3497A Data Acquisition System. This software consists of a set of programs used in determining the ultimate tensile strength and diameter of an individual fiber or filament. With the IDAS it is possible to create a load cell calibration curve and to obtain output in units of grams-force. A program was also created to determine the system compliance in accordance with ASTM procedures. Provisions for complete data analysis are provided through data storage, retrieval and plotting routines. The software gathers data at a rate of 600 points per minute and records and plots Load vs Displacement of the fiber sample.

The IDAS can be used with the INSTRON Model 4206 materials tester or the Naval Postgraduate School Integrated Test system (NPSIT). The programs listed are associated with the INSTRON test system. When using the NPSIT system, the program steps that provide for automatic control of the INSTRON (OUTPUT "704") must be deleted. Crosshead control and pretensioning of the fiber is accomplished manually. A program sub routine is listed in the FTST module and is used to determine fiber diameter using the NPSIT system. Functions keys are defined to provide ready access to commonly used sub routines.

Mr. Jim Nageotte served as the principle computer technician during the development of these programs.

Complete listing of the IDAS programs and a brief description follows.

1. LOAD CELL CALIBRATION MODULE (LDCALB)

"LDCALB" calibrates the load cell to convert the voltage out into grams

```
10 !        ** LDCALB **
20 ! JIM NAGEOTTE  OCT 26 86
30 CLEAR
40 DIM A(100),B(100),Z1(120),Z2
   (120)
50 DISP "LOAD CELL CALIBRATION"
60 CLEAR 709
70 DISP "NUMBER OF CALIBRATION
   POINTS N1="
80 INPUT N1
```

Select the number of calibration points. (six is optimum, maximum ten)

```
90 FOR K=1 TO N1
100 DISP "INPUT LOAD LEVEL"
110 INPUT L(K)
```

Start of loop, once through for each data point.

```
120 W=23 @ E=5000
130 REM :OUTPUT 709 ,"ARVF1VT3VD
   5VA0AE2"
```

Input load level applied to load cell.

```
140 ON TIMER# 1 E GOTO 240
150 I=1
160 OUTPUT 709 ,"AI0"
170 ENTER 709 ; A(I)
```

The 3497 A reads the output voltage A(I). And excitation voltage B(I).

```
180 WAIT 10
190 OUTPUT 709 ,"AI10"
200 ENTER 709 ; B(I)
210 I=I+1
220 WAIT 23
230 GOTO 160
240 OFF TIMER# 1
250 N=I-1
260 P1=0 @ P2=0 @ Q1=0 @ Q2=0
270 X1=0 @ X2=0 @ B0=0
280 FOR I=1 TO N
290 B0=B0+B(I)
300 X1=X1+A(I)/B(I)
310 X2=X2+(A(I)/B(I))^2
```

Fitting the data to a linear function.

```
320 P1=P1+A(I)
330 P2=P2+A(I)^2
340 Q1=Q1+B(I)
350 Q2=Q2+B(I)^2
360 NEXT I
370 E9=P1/N
380 D9=P2/N-E9^2
390 S9=D9^.5
400 C9=ABS(S9/E9*100)
410 E8=Q1/N
420 D8=Q2/N-E8^2
430 S8=D8^.5
440 C8=ABS(S8/E8*100)
450 X5(K)=X1/N
460 B0=B0/N
470 V(K)=X5(K)
480 X6=X2/N
490 D=X6-X5(K)^2
500 S1(K)=D^.5
510 C3=S1(K)/X5(K)
```

```
520 C3=100*C3
530 C3=ABS(C3)
540 PRINT "LOAD=";L(K);" gm"
550 PRINT "MEAN V=";X5(K);" V/V"
560 PRINT "S.D. V=";S1(K);" V/V"
570 PRINT "C.V.(%)=";C3
580 PRINT "L.C. OUTPUT VOLTAGE "
590 PRINT "MEAN V=";E9;" V"
600 PRINT "S.D. V=";S9;" V"
610 PRINT "C.V.(%)=";C9
620 PRINT "EXCITATION VOLTAGE "
630 PRINT "MEAN V=";E8;" V"
640 PRINT "S.D. V=";S8;" V"
650 PRINT "C.V.(%)=";C8
660 PRINT ""
670 NEXT K
680 X1=0 @ Y1=0
690 X3=0 @ X2=0
700 FOR K=1 TO N1
710 X1=X1+V(K)
720 Y1=Y1+L(K)
730 X3=X3+V(K)*L(K)
740 X2=X2+V(K)^2
750 NEXT K
760 X1=X1/N1
770 X2=X2/N1
780 X3=X3/N1
790 Y1=Y1/N1
800 D1=X2-X1^2
810 C1=(X3-X1*Y1)/D1
820 C2=(X2*Y1-X3*X1)/D1
830 PRINT "L=A*V+B"
840 PRINT "A=";C1
850 PRINT "B=";C2
860 R6=0
870 FOR K=1 TO N1
880 G2=(L(K)-C1*V(K)-C2)^2
890 R6=R6+G2
900 NEXT K
910 PRINT "RESIDUAL=";R6
920 DISP "SCREEN GRAPH ROUTINE"
930 DISP "MAX. LOAD="
940 INPUT Y2
950 DISP "MIN. LOAD="
960 INPUT Y1
970 U2=X5(1)
980 U1=X5(1)
990 FOR I=1 TO N1
1000 IF X5(I)>U2 THEN U2=X5(I)
1010 IF X5(I)<U1 THEN U1=X5(I)
1020 NEXT I
1030 PRINT "X MAX (1000V/V)=";U2
     *1000
1040 PRINT "X MIN (1000V/V)=";U1
     *1000
1050 DISP "INPUT MAX FOR X="
```

Begins printing out statistical parameters.

Continues once for each data point (load level).

For least squares method, voltage = V(K) and Load = L(K)

After all load levels are recorded, the program calculates and returns the best fit coefficients, A and B.

Determines the goodness of fit which is expressed by the "residual".

The graph routine plots the load in grams versus voltage out of the load cell. This graph appears on the computer screen and is printed by the thermal printer.

```
1060 INPUT U2
1070 DISP "INPUT MIN FOR X="
1080 INPUT U1
1090 FOR I=1 TO N1
1100 B1(I)=X5(I)*1000
1110 B2(I)=S1(I)*1000
1120 NEXT I
1130 S1=160/(U2-U1)
1140 S2=140/(Y2-Y1)
1150 FOR I=1 TO 5
1160 GRAPH @ GCLEAR
1170 LDIR 0
1180 SCALE -48,308,-76,156
1190 XAXIS 0,32,0,160
1200 YAXIS 0,28,0,140
1210 PEN 1
1220 PENUP
1230 W1=160/(U2-U1)
1240 W2=140/(Y2-Y1)
1250 FOR I=0 TO 5
1260 U=U1+(U2-U1)/5*I
1270 P3=(U-U1)*W1
1280 MOVE P3,-10
1290 LABEL VAL$(U)
1300 NEXT I
1310 FOR I=0 TO 5
1320 Y=Y1+(Y2-Y1)/5*I
1330 Q3=(Y-Y1)*W2
1340 MOVE -23,Q3
1350 LABEL VAL$(Y)
1360 NEXT I
1370 MOVE 40,-23
1380 LABEL "1000*Vout/Vexc"
1390 DEG
1400 MOVE -29,25
1410 LDIR 90
1420 LABEL "FORCE(gm)"
1430 LDIR 0
1440 FOR I=1 TO N1
1450 Z1(I)=(B1(I)-U1)*W1
1460 Z2(I)=(L(I)-Y1)*W2-2
1470 MOVE Z1(I),Z2(I)
1480 LABEL "*"
1490 NEXT I
1500 G1=C1/1000
1510 FOR I=0 TO 101
1520 U=U1+(U2-U1)/100*I
1530 Y=G1*U+C2
1540 IF Y<Y1 OR Y>Y2 THEN 1580
1550 Z1(I)=(U-U1)*W1
1560 Z2(I)=(Y-Y1)*W2
1570 PLOT Z1(I),Z2(I)
1580 NEXT I
1590 COPY
1600 DISP "DO YOU WANT A HARD CO
     PY ON PLOTTER?(Y/N)"
```

This routine plots the graph on the HP Plotter.

```
1610 INPUT Y8$
1620 IF Y8$="N" THEN 2170
1630 PRINTER IS 10
1640 CONTROL 10,5 ; 48
1650 OUTPUT 10 ;"IN;SP1;IP2400,1
     600,8800,6900;"
1660 OUTPUT 10 ;"SC0,1000,0,1000
     "
1670 OUTPUT 10 ;"PU0,0PD0,1000,1
     000,1000,1000,0,0,0PU"
1680 W3=1000/(U2-U1)
1690 W4=1000/(Y2-Y1)
1700 OUTPUT 10 ;"SI0.2,0.3;TL1.5
     ,0"
1710 FOR I=0 TO 5
1720 Y=Y1+(Y2-Y1)/5*I
1730 Y4=(Y-Y1)*W4
1740 Y=INT(Y)
1750 Y4=INT(Y4)
1760 OUTPUT 10 ;"PA 0,";Y4,"YT,"
1770 OUTPUT 10 ;"CP-5,-0.07;LB",
     Y;CHR$(3)
1780 NEXT I
1790 FOR I=0 TO 5
1800 U=U1+(U2-U1)*I/5
1810 U4=(U-U1)*W3
1820 U4=INT(U4)
1830 U=INT(U)
1840 OUTPUT 10 ;"PA";U4,",0;XT,"
1850 OUTPUT 10 ;"CP-1.3,-1;LB";U
     ;CHR$(3)
1860 NEXT I
1870 OUTPUT 10 ;"SI .30,.42"
1880 OUTPUT 10 ;"PA400,0;CP-2,-2
     .3;LB1000*Vout/Vexc";CHR$(3
     )
1890 OUTPUT 10 ;"PA0,460;DI0,1;C
     P-2.6,2.6;LB FORCE (gm) ";C
     HR$(3)
1900 OUTPUT 10 ;"DI;PU"
1910 FOR I=1 TO N1
1920 Z1(I)=(B1(I)-U1)*W3
1930 Z2(I)=(L(I)-Y1)*W4
1940 Z1(I)=INT(Z1(I))
1950 Z2(I)=INT(Z2(I))
1960 OUTPUT 10 ;"PU,";"PA",Z1(I)
     ,Z2(I);"CP-0.1,-0.2;LB*";CH
     R$(3)
1970 NEXT I
1980 OUTPUT 10 ;"PU"
1990 FOR I=0 TO 101
2000 U=U1+(U2-U1)/100*I
2010 Y=G1*U+C2
2020 IF Y<Y1 OR Y>Y2 THEN 2060
2030 Z1(I)=(U-U1)*W3
2040 Z2(I)=(Y-Y1)*W4
2050 OUTPUT 10 ;"PA";Z1(I),Z2(I)
     ;"PD"
```

```
2060 NEXT I
2070 OUTPUT 10 ;"PU0,900,100,900
"
2080 OUTPUT 10 ;"PU"
2090 OUTPUT 10 ;"SI .22,.38"
2100 DISP "ENTER THE LEGEND. ENT
     ER '0' TO EXIT"
2110 INPUT P7$
2120 IF P7$="0" THEN 2150
2130 OUTPUT 10 ;"CP;LB";P7$;CHR$
     (3)
2140 GOTO 2100
2150 PRINTER IS 2
2160 DISP "           END LDCALB"
2170 END
```

The user can enter a label or legend on the finished plot.

"LDCALB" ends.

2. MACHINE SYSTEM COMPLIANCE MODULE (CTST)

The system Compliance module or "CTST" measures the compliance or displacement of the system without a fiber sample.

```
10 !                CTST87
20 !    JIM NAGEOTTE    JAN 13 87
30 !
40 CLEAR
50 DISP @ DISP @ DISP @ DISP @
   DISP "            CTST87"
60 DISP @ DISP "  USE THE FUNCT
   ION KEYS "
70 PRINTER IS 2
80 DIM P(450),L(450),D(450),Z1(
   450),Z2(450)
90 PRINT "IF PROGRAM HALTS, TYP
   E,'CONT 100' TO RETURN TO ME
   NU."
100 PRINT
110 GOTO 130
120 CLEAR
```

This program is menu driven using function keys to access the sub routines. Should execution halt, return to the menu by typing "cont 130".

```
130 ON KEY# 4,"END" GOTO 220
140 ON KEY# 1,"INPUTS" GOSUB 240
150 ON KEY# 2,"ACQUIR" GOSUB 530
160 ON KEY# 3,"DISP" GOSUB 1110
170 ON KEY# 6,"RD_DAT" GOSUB 156
   0
180 ON KEY# 7,"PLOTTR" GOSUB 196
   0
190 ON KEY# 5,"SAV_DAT" GOSUB 17
   10
200 KEY LABEL
210 GOTO 130
```

The keys are defined here.

```
220 CLEAR @ DISP "END CTST87" @
    END
230 !
240 !   ** INPUTS **
250 CLEAR
```

The program will continue to loop on the menu until a function key is depressed.

```
260 ! DISP"ENTER DATA RATE(pts/m
    in)"
270 !    INPUT R
280 R=600 ! PRESET DATA RATE
290 DISP "ENTER ELAPSED TIME (30
     OR 45)"
300 INPUT E0
310 CLEAR @ DISP "ENTER SPEED IN
     MM/MIN"
320 INPUT S
325 PRINT "SPEED = ";S;"MM/MIN"
330 E1=E0*1000
340 DISP "ENTER DATA FILE NAME"
350 INPUT N$
360 CLEAR
376 DISP "P=A*V+B" @ DISP
380 DISP "ENTER 'A' FROM LOCALB
    LISTING"
382 INPUT C3
400 DISP @ DISP "ENTER 'B' FROM
    LOCALB"
410 INPUT B
```

The "INPUTS" sub routine is required first. Input the variables and information needed along with the values of A and B obtained from "LDCALB".

```
420 CLEAR 709
430 OUTPUT 709 "AI10"
440 ENTER 709 ; V
450 DISP "EXCITATION VOLTAGE IS"
    ;V
460 A=ABS(C3/V)
470 A=INT(A*1000)/1000
480 DISP "A=";A
490 DISP "B=";B
500 COPY
505 CLEAR
510 RETURN
```

The HP 3497 A records the excitation voltage applied to the load cell. The equation that translates the load cell voltage into physical units of grams is adjusted for the present excitation voltage.

"INPUTS" is terminated by returning to the menu.

```
520 !
530 !   ** ACQUIR   **
540 IF E0>0 THEN 590
550 BEEP @ BEEP @ BEEP @ CLEAR
560 DISP "'INPUTS' MUST BE RUN F
    IRST!"
570 RETURN
590 CLEAR
600 BEEP
```

The data acquisition sub routine is title "ACQUIR". Acquir checks the time duration selected and if it finds it to be not greater than zero, prompts the operator to run "INPUTS" and returns to the menu.

```
610 FOR I=1 TO 7 @ DISP @ NEXT I
620 DISP "CHECK IEEE BUTTON, MOU
    NT SAMPLE AND BURN " @ DISP
630 DISP "HIT CONT WHEN READY"
640 PAUSE
650 CLEAR @ DISP
653 DISP "FINDING ZERO LOAD"
655 OUTPUT 704 ;"K13,";S
658 OUTPUT 709 ;"AFVR1VT3VD5VA0A
    E2"
```

The program pauses and waits for the operator to hit "cont". At that time a timer is started and data is acquired at a rate of 600 data points per minute.

```
660 OUTPUT 709 ;"AI0"
661 ENTER 709 ; L
662 P=A*L+B
663 IF P<0 THEN GOTO 670
664 OUTPUT 704 ;"K2"
665 WAIT 500
666 OUTPUT 704 ;"K0"
667 GOTO 660
670 CLEAR @ BEEP @ DISP @ DISP "
       MOVING UP"
675 OUTPUT 704 ;"K3"
680 OUTPUT 709 ;"AI0"
685 ENTER 709 ; L
687 P=A*L+B
688 IF P<.06 THEN GOTO 680
691 OUTPUT 704 ;"K21"
694 BEEP @ DISP "TIMER ON"
695 ON TIMER# 1,E1 GOTO 760
700 I=1
710 OUTPUT 709 ;"AI0"
720 ENTER 709 ; L(I)
730 I=I+1
740 WAIT 23
750 GOTO 710
760 OFF TIMER# 1
765 OUTPUT 704 ;"K0"
770 I=I-1
```

Note: OUTPUT "704" provides for automatic control functions to the INSTRON tester. These functions provide for a slight tension in the fiber prior to the start of data acquisition.

The start of the timer is defined at the zero load.

```
780 WAIT 50
790 CLEAR
800 FOR T=1 TO 7 @ DISP @ NEXT T
810 BEEP
830 DISP
840 CLEAR @ DISP " WAIT"
850 N=I
860 PRINT @ PRINT N;"DATA POINTS
    "
865 PRINT
866 OUTPUT 704 ;"K1"
870 FOR I=1 TO N
880 P(I)=A*L(I)+B
890 NEXT I
910 P2=P(1)
920 P1=P(1)
930 FOR I=2 TO N
940 IF P(I)>P2 THEN P2=P(I)
950 IF P(I)<P1 THEN P1=P(I)
970 NEXT I
980 PRINT "P(MAX)=";P2
990 PRINT "P(MIN)=";P1
1000 PRINT
1080 CLEAR
1090 RETURN
1100 !
1110 !     ** DISP GRAPH ON CRT **
1120 PRINT "                    ";N$ @
     PRINT
1130 CLEAR @ DISP "INPUT P(MAX)
     FOR Y AXIS"
1140 INPUT P2
1150 P1=0
1160 GCLEAR
1170 GRAPH
1180 LDIR 0
1190 SCALE -48,208,-36,156
1200 XAXIS 0,32,0,160
1210 YAXIS 0,28,0,140
1220 PEN 1
1230 PENUP
1240 S1=160/(E0/60)/S
1250 S2=140/P2
1260 FOR T=1 TO 5
1270 X=S*T/10
1280 X=INT(X*1000)/1000
1290 X2=X*S1
1300 MOVE X2,-10
1310 LABEL VAL$(X)
1320 NEXT T
1330 FOR T=0 TO 5
1340 P=P2/5*T
1350 P3=P*S2
1360 MOVE -23,P3
1370 LABEL VAL$(P)
1380 NEXT T
1390 MOVE 40,-23
1400 LABEL "DISP (mm)"
```

The voltage is converted to grams force (P(I)).

"ACQUIR" terminates by returning to the menu.

The function key defined as "DISP" calls the sub routine which plots the data on the screen and on the thermal printer.

```
1410 DEG
1420 MOVE -39.25
1430 LDIR 90
```

D(I) is the displacement.

```
1440 LABEL "FORCE (gm)"
1450 LDIR 0
1460 FOR I=1 TO N
1470 D(I)=S*(I/R)
1480 Z1(I)=D(I)*S1
1490 Z2(I)=F(I)*S2
1500 PLOT Z1(I),Z2(I)
```

"DISP" terminates by returning to the menu.

```
1510 NEXT I
1520 COPY
1530 CLEAR
1540 RETURN
```

The load data is read in.

```
1550 !
1560 !    **  READ DATA  **
```

The number of data points saved, the time the test ran and the speed are inputted..

```
1570 CLEAR
1580 DISP "INSERT DATA TAPE"
1590 DISP "HIT CONT"
1600 PAUSE
1610 ASSIGN# 1 TO N$
1620 READ# 1 ; N,E0,S
1630 FOR I=1 TO N
```

A prompt and beep indicate the data has been read in.

```
1640 READ# 1 ; F(I)
1650 NEXT I
1660 ASSIGN# 1 TO *
```

The sub routine is terminated.

```
1670 DISP " DATA READ"
1680 R=600
```

The "SAV-DAT" routine is just the counter part of the above routine. It first checks to see that there is data in the memory to be saved.

```
1690 BEEP
1700 RETURN
1710 !    **  SAV_DAT  **
1720 CLEAR
1730 IF F(3)<>0 THEN GOTO 1790
1740 BEEP @ BEEP @ CLEAR
1750 DISP "NO DATA IN MEMORY"
1760 DISP "HIT CONT"
1770 PAUSE
1780 RETURN
1790 DISP "INSERT DATA TAPE"
1800 DISP
1810 DISP "HIT CONT"
1820 PAUSE
1830 CLEAR @ DISP "WAIT"
```

The memory space is computed and the file opened. The data is then saved. It is in the same form as that read in by "RD-DAT".

```
1840 M=(N+1)*8+50
1850 H=INT(M/256)+1
1860 CREATE N$,H,256
1870 ASSIGN# 1 TO N$
1880 PRINT# 1 ; N,E0,S
1890 FOR I=1 TO N
1900 PRINT# 1 ; F(I)
1910 NEXT I
1920 ASSIGN# 1 TO *
1930 DISP "DATA SAVED"
```

The sub routine is terminated

```
1940 RETURN
1950 !
```

```
1960 !      ** PLOTTER **
1970 CLEAR
1980 DISP "ENTER Y MAX FOR Y AXI
     S"
1990 INPUT Y2
2000 DISP "ENTER Y MIN FOR Y AXI
     S"
2010 INPUT Y1
2020 DISP "ENTER X MAX FOR X AXI
     S"
2030 INPUT X2
2040 DISP "ENTER X MIN FOR X AXI
     S"
2050 INPUT X1
2060 S3=1000/(X2-X1)
2070 S4=1000/(Y2-Y1)
2080 PRINTER IS 10
2090 CONTROL 10,5 ; 48
2100 OUTPUT 10 ;"IN;SP1;IP2400,1
     600,8800,6900;"
2110 OUTPUT 10 ;"SC0,1000,0,1000
     "
2120 OUTPUT 10 ;"PU0,0PD0,1000,1
     000,1000,1000,0,0,0PU"
2130 OUTPUT 10 ;"SI0.2,0.3;TL1.5
     ,0"
2140 FOR I=0 TO 5
2150 Y=INT(Y1+(Y2-Y1)/5*I)
2160 Y4=INT((Y-Y1)*S4)
2170 OUTPUT 10 ;"PA 0,",Y4,"YT;"
2180 OUTPUT 10 ;"CP-5,-0.07;LB";
     Y;CHR$(3)
2190 NEXT I
2200 FOR I=1 TO 5
2210 X=X1+(X2-X1)/5*I
2220 X4=INT((X-X1)*S3)
2230 OUTPUT 10 ;"PA";X4,",0;XT;"
2240 OUTPUT 10 ;"CP-1.3,-1;LB";X
     ;CHR$(3)
2250 NEXT I
2260 OUTPUT 10 ;"SI.30,.42"
2270 OUTPUT 10 ;"PA220,0,CP4,-2.
     3;LBDISPLACEMENT (mm)";CHR$
     (3)
2280 OUTPUT 10 ;"PA0,460;DI0,1;C
     P-2.6,2.60;LB FORCE (gm)";C
     HR$(3)
2290 OUTPUT 10 ;"DI;PU"
2300 FOR I=1 TO N
2310 D(I)=S*I/R
2320 Z1(I)=INT((D(I)-X1)*S3)
2330 Z2(I)=INT((P(I)-Y1)*S4)
2340 OUTPUT 10 ;"PA",Z1(I),Z2(I)
     ;"PD"
2350 NEXT I
2360 OUTPUT 10 ;"PU0,900,100,900
     "
```

The "PLOTTER" function is design to create a plot on the HP Plotter.

Select the maximum and minimum values for the X and Y axis on the plot.

This plot will be on the HP plotter similar to the plot on the CRT screen.

The lables for the axis are put in place.

Here displacement is represented by D(I) while P(I) is load.

```
2370 OUTPUT 10 ;"PU"
2380 OUTPUT 10 ;"SI 22, 38"
2390 DISP "LOCATE PEN FOR LEGEND
     "
2400 DISP @ DISP "ENTER THE LEGE
     ND YOU WANT."
2410 DISP "ENTER A '0' WHEN DONE
     "
2420 INPUT P$
2430 IF P$="0" THEN 2460
2440 OUTPUT 10 ;"CP;LB";P$;CHR$(
     3)
2450 GOTO 2400
2460 PRINTER IS 2
2470 RETURN
2535 CLEAR 709
```

After the plot is completed, the pen moves to the upper left corner where a legend may be created.

The program is completed and returns to the menu.

3. QUADRATIC FIT MODULE (QFIT)

"QFIT" fits a quadratic equation to the compliance data obtained from "MCTST".

```
10 !     **  QFIT  **       10 24 86
20 !      JIM HAGEOTTE
30 !
40 !  FIT THE MCTST DATA BY A QUADRATIC EQUATION
50 !
60 CLEAR
70 PRINTER IS 2
80 SHORT P(450),Z1(450),Z2(450)
90 DIM E(2,2),F(2),G(2),D(450)
100 BEEP @ DISP "INSERT DATA TAPE"
110 DISP "INPUT FILE NAME"
120 INPUT N$
130 ASSIGN# 1 TO N$
140 READ# 1 , N,E0,S
150 FOR I=1 TO N
160 READ# 1 , P(I)
170 NEXT I
180 ASSIGN# 1 TO *
190 R=600 ! DATA SAMPLING RATE(pnts/min)
200 FOR I=1 TO N
210 D(I)=I*S/R
220 NEXT I
230 DISP "DO YOU WANT TO DISP THE GRAPH ON SCREEN (Y/N)?"
240 BEEP
250 INPUT A$
260 IF A$="Y" THEN GOSUB 1020
270 !
280 DISP "DO YOU WANT A HARD COPY ON PLOTTER?(Y/N)"
290 INPUT A$
300 IF A$="Y" THEN GOSUB 1600
310 !
320 DISP "Q FIT SUBROUTINE"
330 DISP "COMPUTING  ABOUT 2 MINUTES "
```

Input file name. Use the file stored by "MCTST".

A graph or plot at this point would give results identical to the output of "MCTST".

The "QFIT" sub routine requires about two minutes. The exact time depends on the number of data points to be fitted.

```
340 E(0,0)=N
350 E(0,1)=0
360 E(0,2)=0
370 E(1,1)=0
380 E(1,2)=0
390 E(2,2)=0
400 FOR I=21 TO N
410 E(0,2)=E(0,2)+P(I)^2
420 NEXT I
430 FOR I=1 TO N
440 E(0,1)=E(0,1)+P(I)
441 E(1,2)=E(1,2)+P(I)^2*(P(I)*N)
```

Initializing the matrix

Least square method

```
520 E(2,2)=E(2,2)+P(I)^2*(P(I)^2
    *N)
530 NEXT I
535 E(1,1)=E(0,2)
540 E(1,2)=E(1,2)/N
550 E(2,2)=E(2,2)/N
570 G(0)=0 @ G(1)=0 @ G(2)=0
580 FOR I=1 TO N
600 G(0)=G(0)+D(I)
630 G(1)=G(1)+D(I)*P(I)
660 G(2)=G(2)+D(I)*P(I)^2
670 NEXT I
680 DISP "MATRIX OPERATION"
690 E(1,0)=E(0,1)
700 E(2,0)=E(0,2)
```

By symmetry

```
710 E(2,1)=E(1,2)
720 MAT DISP E
730 MAT F=SYS(E,G)
740 PRINTER IS 2
750 PRINT "        ";N$ @ PRINT
760 PRINT "P=E+F*DELTA+G*DELTA^2
    "
```

The best fit coefficients E, F, and G are returned and printed out.

```
770 PRINT "E=";F(0)
780 PRINT "F=";F(1)
790 PRINT "G=";F(2)
800 DISP "P=E+F*DELTA+G*DELTA^2"
810 DISP "E=";F(0)
820 DISP "F=";F(1)
830 DISP "G=";F(2)
840 MAT PRINT F
850 E=F(0)
860 F=F(1)
870 G=F(2)
880 CLEAR @ DISP "COMPUTING"
890 FOR I=1 TO N
900 D(I)=E+F*P(I)+G*P(I)^2
910 NEXT I
920 BEEP
930 DISP "DO YOU WANT A COPY OF
    ESTIMATED CURVE ON THE SCREE
    N ?(Y/N)"
```

The coefficients are then used to calculate the estimated curve of displacement as a function of load P(I).

```
940 INPUT A$
950 IF A$="Y" THEN GOSUB 1020
960 DISP "DO YOU WANT A HARD COP
    Y OF ESTIMATED CURVE ON PLOT
    TER?(Y/N)"
970 INPUT A$
980 IF A$="Y" THEN GOSUB 1600
990 BEEP
1000 DISP "END OF QFIT"
1010 END
```

A plot of this curve , shows a smooth representation of the original curve.

The main program ends.

```
1020 !   ** SCREEN PLOT **
1030 DISP "DISPLAY THE RESULT ON
      THE SCREEN"
1040 PRINT "                ";N$
1050 PRINT
1060 Y2=P(1)
```

The screen plot routine is the same as that used in "MCTST" and plots the graph on the CRT screen and thermal printer.

```
1070 Y1=P(1)
1080 FOR I=2 TO N
1090 IF P(I)>Y2 THEN Y2=P(I)
1100 IF P(I)<Y1 THEN Y1=P(I)
1110 NEXT I
1120 PRINT "Y MAX=";Y2
1130 DISP "INPUT Y MAX FOR Y AXIS"
1140 INPUT Y2
1150 PRINT "Y MIN=";Y1
1160 DISP "INPUT Y MIN FOR Y AXIS"
1170 INPUT Y1
1180 DISP "ENTER X MAX FOR X AXIS"
1190 INPUT X2
1200 DISP "ENTER X MIN FOR X AXIS"
1210 INPUT X1
1220 GRAPH
1230 GCLEAR
1240 LDIR 0
1250 SCALE -48,208,-36,156
1260 XAXIS 0,32,0,160
1270 YAXIS 0,28,0,140
1280 PEN 1
1290 PENUP
1300 X1=0
1310 S1=160/(X2-X1)
1320 S2=140/(Y2-Y1)
1330 FOR I=1 TO 5
1340 X=X2/5*I
1350 X3=(X-X1)*S1
1360 MOVE X3,-10
1370 LABEL VAL$(X)
1380 NEXT I
1390 FOR I=0 TO 5
1400 Y=Y1+(Y2-Y1)/5*I
1410 Y3=(Y-Y1)*S2
1420 MOVE -23,Y3
1430 LABEL VAL$(Y)
1440 NEXT I
1450 MOVE 40,-23
1460 LABEL "DISPLACEMENT (mm)"
1470 DEG
1480 MOVE -29,25
1490 LDIR 90
1500 LABEL "FORCE(gm)"
1510 LDIR 0
1520 FOR I=1 TO N
1530 Z1(I)=(D(I)-X1)*S1
1540 Z2(I)=(P(I)-Y1)*S2
1550 PLOT Z1(I),Z2(I)
1560 NEXT I
1570 COPY
1580 RETURN
1590 !
1600 !     **   PLOTTER   **
```

The X axis or displacement is represented by D(I) while the Y axis or load is represented by P(I).

The plotter routine plots the graph on the HP Plotter.

```
1610 UISP "ENTER Y MAX" @ INPUT
     Y2
1620 DISP "ENTER Y MIN" @ INPUT
     Y1
1630 DISP "ENTER X MAX" @ INPUT
     X2
1640 DISP "ENTER X MIN" @ INPUT
     X1
1650 S3=1000/(X2-X1)
1660 S4=1000/(Y2-Y1)
1670 PRINTER IS 10
1680 CONTROL 10,5 ; 48
1690 OUTPUT 10 ;"IN;SP1;IP2400,1
     600,8800,6900;"
1700 OUTPUT 10 ;"SC0,1000,0,1000
     "
1710 OUTPUT 10 ;"PU0,0PD0,1000,1
     000,1000,1000,0,0,0PU"
1720 OUTPUT 10 ;"SI0.2,0.3;TL1.5
     ,0"
1730 FOR I=0 TO 5
1740 Y=INT(Y1+(Y2-Y1)/5*I)
1750 Y4=INT((Y-Y1)*S4)
1760 OUTPUT 10 ;"PA 0,",Y4,"YT;"
1770 OUTPUT 10 ;"CP-5,-0.07;LB";
     Y;CHR$(3)
1780 NEXT I
1790 FOR I=1 TO 5
1800 X=X1+(X2-X1)/5*I
1810 X4=(X-X1)*S3
1820 X4=INT(X4)
1830 OUTPUT 10 ;"PA",X4,",0;XT;"
1840 OUTPUT 10 ;"CP-1.3,-1;LB";X
     ;CHR$(3)
1850 NEXT I
1860 OUTPUT 10 ;"SI.30,.42"
1870 OUTPUT 10 ;"PA370,0;CP-2,-3
     .3;LBDISPLACEMENT (mm)";CHR
     $(3)
1880 OUTPUT 10 ;"PA0,460;DI0,1;C
     P-2.6,2.60;LB FORCE (gm)";C
     HR$(3)
1890 OUTPUT 10 ;"DI;PU"
1900 FOR I=1 TO N
1910 Z1(I)=INT((D(I)-X1)*S3)
1920 Z2(I)=INT((P(I)-Y1)*S4)
1930 OUTPUT 10 ;"PA",Z1(I),Z2(I)
     ;"PD"
1940 NEXT I
1950 OUTPUT 10 ;"PU0,900,100,900
     "
1960 OUTPUT 10 ;"PU"
1970 OUTPUT 10 ;"SI.22,.30"
1980 DISP "INPUT THE LEGEND YOU
     WANT? TYPE '0' WHEN DONE"
1990 INPUT P$
2000 IF P$="0" THEN 2030
```

A label or legend can be entered here.

4. FIBER TEST MODULE (FTST)

```
10 !              FTST87
20 !    JIM NAGECTTE    JAN 13 87
30 !
40 CLEAR
45 DISP "          FTST87 "
50 DISP @ DISP "YOU MUST RUN CA
   LB BEFORE PLOT OR SAV-DAT!"
60 DISP @ DISP " USE THE FUNCTI
   ON KEYS."
70 SHORT F(450),L(450),T
80 SHORT D1(450),D2(450),D3(450
   ),D(450)
90 SHORT Z1(450),Z2(450)
100 GOTO 120
110 CLEAR
120 ON KEY# 4,"GRAF" GOSUB 2700
130 ON KEY# 1,"INPUTS" GOSUB 230
140 ON KEY# 2,"ACQUIR" GOSUB 600
150 ON KEY# 6,"RD_DAT" GOSUB 117
    0
160 ON KEY# 7,"PLOT" GOSUB 1320
170 ON KEY# 5,"SAV_DAT" GOSUB 20
    30
180 ON KEY# 8,"CALB" GOSUB 1830
185 ON KEY# 3,"AREA" GOSUB 2500
190 KEY LABEL
200 GOTO 120
210 CLEAR @ DISP "END FTST87" @
    END
220 !
230 !  ** INPUTS **
240 CLEAR @ !  DISP"ENTER DATA R
    ATE(PTS/MIN)"
250 !  INPUT R
260 R=600 ! PRESET DATA RATE
270 DISP "ENTER ELAPSED TIME (30
     OR 45)"
280 INPUT E0
290 CLEAR @ DISP "ENTER SPEED (m
    m/min)"
300 INPUT S
310 CLEAR @ DISP "ENTER GAGE LEN
    GTH (mm)"
320 INPUT G1
330 E1=E0*1000
332 CLEAR
350 DISP
360 DISP "ENTER 'A' FROM LDCALB
    LISTING"
370 INPUT C3
380 DISP "ENTER 'B' FROM LDCALB"
390 INPUT B
400 CLEAR 709
410 OUTPUT 709 ;"AI10"
```

The Fiber Test is known as "FTST".

"CALB" program must be run before the PLOT" or "SAV-DAT" routines.

The function keys are defined.

The program loops here until a function is selected.

The "INPUTS" routine is required first.

The gage length is to be used in computing strain.

```
420 ENTER 709 ; V
430 DISP "EXCITATION VOLTAGE IS"
    ;V
440 A=ABS(C3/V)
450 A=INT(A*1000)/1000
460 DISP "A=";A
470 DISP "B=";B
475 DISP "SPEED =";S;"MM/MIN"
480 COPY
490 CLEAR @ DISP "ENTER COMPLIAN
    CE COEFFECIENTS"
```

The excitation voltage is read and the calibration adjusted to compensate for any voltage drift.

```
500 DISP "E= "
510 INPUT E
520 DISP "F= "
530 INPUT F
540 DISP "G= "
550 INPUT G
560 PRINT "E=";E @ PRINT "F=";F
570 PRINT "G=";G
580 CLEAR
590 RETURN
600 !
610 !   ** ACQUIR  **
```

The compliance coefficients are entered so that a matching compliance curve may be generated and then subtracted from the total deformation, yielding the true displacement of the sample.

```
620 IF E0>0 THEN 660
630 BEEP @ CLEAR
640 DISP "'INPUTS' MUST BE RUN F
    IRST!"
650 RETURN
660 CLEAR
690 BEEP
700 FOR I=1 TO 7 @ DISP @ NEXT I
710 DISP "CHECK IEEE BUTTON, MOU
    NT SAMPLE AND BURN"
720 DISP "HIT CONT WHEN READY"
722 PAUSE
723 CLEAR
```

The routine ends and returns to the menu.

The "ACQUIR" routine is the actual data acquisition routine.

The program checks to see that the inputs have been entered and provides prompts if no input data can be found.

```
724 DISP "FINDING ZERO LOAD"
725 OUTPUT 704 ;"K13,";S
730 OUTPUT 709 ;"ARVR1VT3VD5VA0A
    E2"
731 OUTPUT 709 ;"AI0"
732 ENTER 709 ; L
733 P=A*L+B
734 IF P<0 THEN GOTO 755
735 OUTPUT 704 ;"K2"
736 WAIT 500
737 OUTPUT 704 ;"K0"
738 GOTO 731
750 CLEAR @ BEEP @ DISP "MOVING
    UP"
755 OUTPUT 704 ;"K3"
756 OUTPUT 709 ;"AI0"
757 ENTER 709 ; L
759 P=A*L+B
```

The OUTPUT "704" codes provide for automatic control of the Instron tester. Initially the cross head is adjusted to provide for slight tension in the fiber, after which the timer will start and data collection will begin.

```
760 IF P< 06 THEN GOTO 756
762 OUTPUT 704 ;"K21"
765 BEEP @ DISP "TIMER ON"
768 ON TIMER# 1,E1 GOTO 830
770 I=1
780 OUTPUT 709 ;"AI0"
790 ENTER 709 ; L(I)
800 I=I+1
810 WAIT 23
820 GOTO 780
830 OFF TIMER# 1
835 OUTPUT 704 ;"K0"
840 I=I-1
850 WAIT 50
860 CLEAR
870 FOR T=1 TO 7 @ DISP @ NEXT T
880 BEEP @ CLEAR @ DISP "CHECK E
    XTENSION     HIT CONT"
890 PAUSE
900 OUTPUT 704 ;"K1"
910 N=I
920 DISP N;"DATA POINTS"
930 DISP "COMPUTING "
940 FOR I=1 TO N
950 P(I)=A*L(I)+B
960 NEXT I
970 P2=P(1) @ P1=P(1)
980 FOR I=2 TO N
990 IF P(I)>P2 THEN K=I
1000 IF P(I)>P2 THEN P2=P(I)
1010 IF P(I)<P1 THEN P1=P(I)
1030 NEXT I
1060 DISP "P(max)=";P2
1070 D4=S*(K/R)*(1/G1)*100
1080 DISP "D%";D4,K
1090 PRINT "P(MAX)= ";P2
1095 PRINT "D% = ";D4,k
1150 RETURN
1160 !
1170 !    **  READ DATA  **
1180 CLEAR
1190 DISP "ENTER FILE NAME"
1195 DISP "YOU MUST HAVE INPUTS
     BEFORE YOU CAN PLOT READ DA
     TA"
1200 INPUT N$
1210 ASSIGN# 1 TO N$
1220 READ# 1 ; N,E0,S,G1,k
1230 FOR I=1 TO N
1240 READ# 1 ; P(I),D(I)
1250 NEXT I
1260 ASSIGN# 1 TO *
1270 Y2=P(K) @ X2=D(K)
1280 DISP " DATA HAS BEEN READ"
1290 BEEP
1300 RETURN
```

The voltage from the load cell is converted to physical units of grams. Here the tension level is adjusted.

After a quick analysis of some key data points are printed out to provide a indication of the nature of the data gathered.

The sub routine returns to the main loop.

The "RD-DATA" routine allows you to read in a data file that had been stored earlier and then plot results.

It reads:

Number of data points,	N
Elapsed time of test,	E0
Speed of test,	S
Gage length tested,	G1
Point of Max load,	K
Load and Strain,	P(I), D(I)

```
1310 !
1320 !       ** PLOTTER **
1330 CLEAR
1340 DISP "ENTER Y MAX FOR Y AXI
     S"
1350 INPUT Y2
1360 DISP "ENTER Y MIN FOR Y AXI
     S"
1370 INPUT Y1
1380 DISP "ENTER X MAX FOR X AXI
     S"
1390 INPUT X2
1400 DISP "ENTER X MIN FOR X AXI
     S"
1410 INPUT X1
1420 S3=1000/(X2-X1)
1430 S4=1000/(Y2-Y1)
1440 PRINTER IS 10
1450 CONTROL 10 5 , 48
1460 OUTPUT 10 ;"IN;SP1;IP2400,1
     600,8800,6900;"
1470 OUTPUT 10 ;"SC0,1000,0,1000
     "
1480 OUTPUT 10 ;"PU0,0PD0,1000,1
     000,1000,1000,0,0,0PU"
1490 OUTPUT 10 ;"SI0.2,0.3;TL1.5
     ,0"
1500 FOR I=0 TO 5
1510 Y=INT(Y1+(Y2-Y1)/5*I)
1520 Y4=INT((Y-Y1)*S4)
1530 OUTPUT 10 ;"PA 0,",Y4,"YT;"
1540 OUTPUT 10 ;"CP-5,-0.07;LB";
     Y;CHR$(3)
1550 NEXT I
1560 FOR I=1 TO 5
1570 X=X1+(X2-X1)/5*I
1580 X4=INT((X-X1)*S3)
1590 OUTPUT 10 ;"PA";X4,",0;XT;"
1600 OUTPUT 10 ;"CP-1.3,-1;LB";X
     ;CHR$(3)
1610 NEXT I
1620 OUTPUT 10 ;"SI.30,.42"
1630 OUTPUT 10 ;"PA220,0;CP6,-2.
     3;LBSTRAIN(%)";CHR$(3)
1640 OUTPUT 10 ;"PA0,460;DI0,1;C
     P-2.6,2.60;LB FORCE (gm)";C
     HR$(3)
1650 OUTPUT 10 ;"DI;PU"
1660 FOR I=1 TO N
1665 D(I)=S*I/R
1670 Z1(I)=INT((D(I)-X1)*S3)
1680 Z2(I)=INT((P(I)-Y1)*S4)
1690 OUTPUT 10 ;"PA",Z1(I),Z2(I)
     ;"PD"
```

Program returns to the menu.

The "Plotter" routine is the same as used in "MCTST".

Here, D(I) represents the strain while the load is at P(I).

```
1700 NEXT I
1710 OUTPUT 10 ;"PA0,900,100,900
     "
1720 OUTPUT 10 ;"PU"
1730 OUTPUT 10 ;"SI .22, 38"
1740 DISP @ DISP "ENTER THE LEGE
     ND YOU WANT "
1750 DISP "ENTER A '0' WHEN DONE
     "
1760 INPUT P$
1770 IF P$="0" THEN 1800
1780 OUTPUT 10 ;"CP;LB";P$;CHR$(
     3)
```

Label the graph for identification.

```
1790 GOTO 1740
1800 PRINTER IS 2
1810 RETURN
1820 !
1830 !     *** CALB ***
1840 IF F<>0 THEN GOTO 1870
1850 CLEAR @ DISP "NEED INPUTS!"
1860 RETURN
1870 CLEAR @ BEEP @ DISP "DATA C
     ONVERSION TO PHYSICAL UNIT"
```

The routine returns to the menu.

```
1880 FOR I=1 TO K
1890 D1(I)=S*I/R
1900 D2(I)=G*P(I)^2+F*P(I)+E
1910 D3(I)=D1(I)-D2(I)
1920 D(I)=D3(I)/G1*100 ! % STRAI
     N
```

"CALB" is the calibration routine where the final output is true displacement and strain of the fiber sample.

```
1930 NEXT I
1940 FOR I=K+1 TO N
1950 D1(I)=S*I/R
1960 D2(I)=D2(K)
1970 D3(I)=D1(I)-D2(I)
1980 D(I)=D3(I)/G1*100 ! % STRAI
     N
```

D1 is the total displacement. D2 is the displacement of the system as a function of the load, P1, calculated using the coefficients E, F, and G.
D3 = D1 -D2, the true displacement of the fiber sample.
D is the strain in percent .

```
1990 NEXT I
2000 PRINT "P(MAX)=";P(K);K
2010 PRINT "D% =";D(K)
2015 CLEAR @ DISP "CALB COMPLETE
     "
2020 RETURN
2030 ! *** STORE ADJUSTED DATA *
     *
2040 IF D(30)<>0 THEN 2070
2050 BEEP @ DISP " NO DATA PRESE
     NT"
```

Return to the menu.

```
2060 RETURN
2070 CLEAR @ BEEP @ DISP "INSERT
      DATA CARTRIDGE"
2080 DISP "ENTER FILE NAME."
```

This sub routine is used to store the adjusted data calculated in the CALB sub routine.

```
2090 INPUT N$
2100 CLEAR @ DISP "STORING DATA"
2110 M=2*(N+1)*8+50
2120 H=INT(M/256)+1
2130 CREATE N$,H,256
2140 ASSIGN# 1 TO N$
2150 PRINT# 1 ; N,E0,S,G1,K
```

```
2160 FOR I=1 TO N
2170 PRINT# 1 ; P(I),D(I)
2180 NEXT I
2190 ASSIGN# 1 TO *
2200 CLEAR @ DISP "DATA STORED"
2210 BEEP
2220 RETURN
2500 !
2510 ! **      AREA     **
2520 CLEAR @ DISP "COMPUTING ARE
     A UNDER P/D CURVE."
2530 T=0
2540 FOR I=1 TO K-1
2550 A1=(P(I)+P(I+1))/2
2560 A2=A1*(D(I+1)-D(I))
2570 T=T+A2
2580 NEXT I
2590 PRINT "AREA UNDER THE P/D C
     URVE=";T;"am%"
2595 PRINT
2600 IF N$<>"" THEN PRINT ;"
         ",N$
2610 CLEAR @ DISP "AREA COMPUTED
     " @ RETURN
2700 !
2710 !   **DISP CRT GRAPH**
2720 PRINT "                ";N$ @
     PRINT
2730 CLEAR @ DISP "INPUT P(MAX)
     FOR Y AXIS"
2740 INPUT P2
2750 P1=0
2760 GCLEAR
2780 GRAPH
2790 LDIR 0
2800 SCALE -48,208,-36,156
2810 XAXIS 0,32,0,160
2820 YAXIS 0,28,0,140
2830 PEN 1
2840 PENUP
2850 S1=160/(E0/60)/S
2860 S2=140/P2
2870 FOR T=1 TO 5
2880 X=S*T/10
2890 X=INT(X*1000)/1000
2900 X2=X*S1
2910 MOVE X2,-10
2920 LABEL VAL$(X)
2930 NEXT T
2940 FOR T=0 TO 5
2950 P=P2/5*T
2960 P3=P*S2
2970 MOVE -23,P3
2980 LABEL VAL$(P)
2990 NEXT T
3000 MOVE 40,-23
3010 LABEL "DISP(MM)"
```

Return to menu

AREA calculates the are under the load versus displacement curve.

This sub routine provides for a graphical output on the CRT screen

```
3020 DEG
3030 MOVE -29.25
3040 LDIR 90
3050 LABEL "FORCE (gm)"
3060 LDIR 0
3070 FOR I=1 TO N
3080 D(I)=S*(I/R)
3090 Z1(I)=D(I)*S1
3100 Z2(I)=P(I)*S2
3110 PLOT Z1(I),Z2(I)
3120 NEXT I
3130 COPY
3140 CLEAR
3150 RETURN
3200 !      **DIAMETER**
3210 ! DIAMETER PROGRAM
3220 CLEAR
3230 ! W=WAVE LENGTH, N$=FIBER D
     ESIGNATION, C1=DELTAC AND S
     3=SEM EQUIVELENT VALUE
3240 DISP "THIS PROGRAM FINDS TH
     E FINAL DIAMETER"
3250 W=.0000006328
3251 N=1
3252 C=115
3253 L=698.1
3254 DISP "ENTER FIBER DESIGN"
3260 INPUT N$
3270 PRINT "FIBER NO    ";N$
3280 FOR I=1 TO N
3290 DISP "ENTER MICRO READING"
3300 INPUT C1
3310 Q=W*2*L/(C1+C)
3320 Q=INT(Q*1.E13)/10000000
3330 PRINT "NPSLT VALUE = ";Q
3340 ! CONVERT TO SEM VALUE
3350 Q1=.89*Q+.3614
3360 Q1=INT(Q1*10000000)/1000000
     0
3370 PRINT "FIBER DIAMETER= ";Q1
     ;"                      MICRO
     NS"
```

This sub routine is used when determining fiber diameter. it provides for the input of the fiber designation and micrometer readings.

The fiber diameter is determined based on an average of the micrometer readings and corrected in accordance with the SEM cal curve.

5. LOAD CELL TEST MODULE (LDTST)

"LDTST" is a short utility to test the load cell for proper operation and reproducibility.

```
10 ! ** LDTST **
20 ! TAKES 25 READINGS FROM LO
   ADCELL AND PRINTS AVERAGE
30 CLEAR
40 DISP "ENTER A"
50 INPUT A1
60 DISP "ENTER B"
70 INPUT B1
80 CLEAR
90 CLEAR 709
100 OUTPUT 709 ;"AI10"
110 ENTER 709 ; V
120 A=A1/V
125 B=B1
130 P1=0
140 FOR I=1 TO 25
150 OUTPUT 709 ;"AI0"
160 ENTER 709 , L
170 P=L*A+B
175 P=INT(P*1000)/1000
180 DISP P,
190 P1=P1+P
200 NEXT I
210 PRINT "V(out)=",V
220 PRINT "LOAD =";P1/25,"(gm)"
230 BEEP
240 PRINT
250 DISP "SET LOAD, HIT CONT"
260 PAUSE
270 PRINT
280 GOTO 80
```

Load cell output voltage is recorded 25 times then converted to grams.
The average load is printed.

The program pauses and a load level may be changed.

Press continue after installing new load.

Press "pause" or "reset" to leave program loop.

6. LOAD STORAGE MODULE (LOADSTOR)

"LOADSTOR" is a utility program to allow for quick storage or access to data files. This is useful for the transfer of files.

"RD-C" and "SAV-C" read and save the "MCTST" files.

"RD-F" and "SAV-F" read and save the "FTST" files.

After loading a data file, you may press "END" and then examine or list the data in the command mode. Refer to the print out for variable names. When action complete, re-enter the program without losing the data by entering "cont 50".

```
10 ! ** LOSTOR **
20 ! LOADS AND STORES DATA FILE
     TAPES CREATED WITH FTST AND
     MCTST
30 ! JIM NAGEOTTE  OCT 27 86
40 DIM F1(450),D(450)
45 GOSUB 5000
50 CLEAR
60 ON KEY# 1,"RD-C" GOSUB 1000
70 ON KEY# 2,"SAV-C" GOSUB 2000
80 ON KEY# 3,"RD-F" GOSUB 3000
90 ON KEY# 4,"SAV-F" GOSUB 4000
100 ON KEY# 8,"END" GOTO 150
110 KEY LABEL
120 GOTO 60
150 END
1000 !     ** RD-C **
1010 CLEAR @ BEEP
1020 DISP " READ COMPLIANCE FILE
     "
1030 DISP
1040 DISP "INSERT DATA TAPE"
1050 DISP "ENTER FILE NAME"
1060 INPUT N$
1070 CLEAR @ DISP "READING DATA"
1080 ASSIGN# 1 TO N$
1090 READ# 1 ; N,E0,S
1100 FOR I=1 TO N
1110 READ# 1 ; F1(I)
1120 NEXT I
1130 ASSIGN# 1 TO *
1140 CLEAR
1150 DISP "DATA READ"
1160 BEEP
1170 RETURN
2000 ! ** SAVE C **
2010 CLEAR @ DISP "SAVE COMPLIAN
     CE FILE"
2020 DISP
2030 DISP "INSERT DATA TAPE"
2040 BEEP
2050 DISP "ENTER FILE NAME"
2060 INPUT N$
2070 CLEAR
2080 DISP "SAVING DATA"
2090 M=(N+1)*8+50
2100 H=INT(M/256)+1
2110 CREATE N$,H,256
2120 ASSIGN# 1 TO N$
2130 PRINT# 1 ; N,E0,S
2140 FOR I=1 TO N
2150 PRINT# 1 ; F1(I)
2160 NEXT I
2170 ASSIGN# 1 TO *
2180 CLEAR
```

```
2190 DISP "DATA SAVED"
2200 BEEP
2210 RETURN
3000 !     ** RD-F **
3010 CLEAR @ BEEP
3020 DISP " READ FIBER TEST FILE "
3030 DISP
3040 DISP "INSERT DATA TAPE"
3050 DISP "ENTER FILE NAME"
3060 INPUT N$
3070 CLEAR @ DISP "READING DATA"
3080 ASSIGN# 1 TO N$
3090 READ# 1 ; N,E0,S,G1,K
3100 FOR I=1 TO N
3110 READ# 1 ; P1(I),D(I)
3120 NEXT I
3130 ASSIGN# 1 TO *
3140 CLEAR
3150 DISP "DATA READ"
3160 BEEP
3170 RETURN
4000 ! ** SAVE F **
4010 CLEAR @ DISP "SAVE FIBER TEST FILE"
4020 DISP
4030 DISP "INSERT DATA TAPE"
4040 BEEP
4050 DISP "ENTER FILE NAME"
4060 INPUT N$
4070 CLEAR
4080 DISP "SAVING DATA"
4090 M=2*(N+1)*8+50
4100 H=INT(M/256)+1
4110 CREATE N$,H,256
4120 ASSIGN# 1 TO N$
4130 PRINT# 1 ; N,E0,S,G1,K
4140 FOR I=1 TO N
4150 PRINT# 1 ; P1(I),D(I)
4160 NEXT I
4170 ASSIGN# 1 TO *
4180 CLEAR
4190 DISP "DATA SAVED"
4200 BEEP
4210 RETURN
5000 ! ** INFO **
5010 PRINT "AFTER 'PAUSE' OR 'END' YOU MAY CONTINUE WITHOUT DATA LOSS BY TYPING:"
5020 PRINT "'CONT 50'"
5030 PRINT
5040 PRINT "C FILES CONTAIN N,E0,S AND P1(I)"
5050 PRINT
5060 PRINT "F FILES CONTAIN N,E0,S,G1,K AND P1(I),D(I)"
5070 PRINT @ PRINT
```

APPENDIX C. DETERMINING BUNDLE PRELOAD

Before composite preload level can be determined a mathematical model, based on individual fiber data, must be developed to study the effects of gage length on the strength distribution. Previous studies have provided conclusive results that composite strength is a function of gage length. In order to predict the behavior of a 254 millimeter strand, the results of the fiber tests, (gage length = 50 millimeter) must be examined and equated to a sample that is 254 millimeters long.

Results from a previous study [Ref. 7], which examined the affects of proof testing Kevlar-49 at elevated temperatures will be used to verify the mathematical model and to establish an estimated preload level.

1. MATHEMATICAL CORRECTION FOR GAGE LENGTH

$$F1 = 1 - \exp\{-(\sigma/\beta_1)^{\alpha_1}\} \qquad \text{for gage length} = l_1 \qquad (4)$$

$$R1 = \exp\{-(\sigma/\beta_1)^{\alpha_1}\} \qquad (5)$$

$$l_2 / l_1 = n \qquad \text{for gage length} = l_2$$

$$R_1 = \prod R_1 R_2 \ldots = (R_1)^n$$

$$= [\exp\{-(\sigma/\beta_1)^{\alpha_1}\}]^n$$

$$= \exp\{-n(\sigma/\beta_1)^{\alpha_1}\} = \exp\{-n(\sigma/\beta_2)^{\alpha_2}\}$$

$$= \exp\{-n(\sigma^{\alpha_1}/\beta_1^{\alpha_1})\} = \exp\{-n(\sigma^{\alpha_2}/\beta_2^{\alpha_2})\}$$

$$\sigma^{\alpha_1} \quad \sigma^{\alpha_2} \qquad \alpha_1 \quad \alpha_2$$

$$n/\beta_1^{\alpha_1} = 1/\beta_2^{\alpha_2}$$

$$(\beta_1/\beta_2)^{\alpha_1} = n = l_1/l_2$$

$$(\beta_1/\beta_2) = l_2^{(1/\alpha_1)} / l_1^{(1/\alpha_1)}$$

$$(\beta_2/\beta_1) = (l_1/l_2)^{(1/\alpha_1)}$$

Results:

$$\boldsymbol{\beta_2 = \beta_1 (l_1/l_2)^{(1/\alpha_1)}} \qquad (6)$$

Mathematically, equation (6) provides for the beta adjustment for gage length .

2. KEVLAR - 49 MODEL

Based on original test data, Table VII., the beta for strain $\beta\varepsilon$ can be corrected for various gage lengths.

TABLE VII . ORIGINAL TEST DATA

Material	G.L.(mm)	α	β(gm)	(gm/$\mathcal{E}$)
Kevlar -49	50	6.7	38.9	$1.3x10^3$
Kevlar $_{(25°C)}$	254	25.9	$9.74x10^3$	$4.0x10^5$
Kevlar $_{(70°C)}$	254		$9.50x10^3$	$3.0x10^5$

Using the test data for a 50 mm. fiber and substituting β_ε for β_l in equation (6), where;

$$\beta_\varepsilon = \frac{\beta_L}{E}$$

$$\beta_{\varepsilon 2} = \beta_{\varepsilon 1} (l_1 / l_2)^{(1/\alpha_1)}$$

Correction to gage lengths can be made, see Table VIII.

TABLE VIII. CORRECTED $\beta\varepsilon$ OF KEVLAR - 49 FOR VARIOUS GAGE LENGTHS δ.

Delta mm (ineffective length)	δ	.1	.5	1	10	50	254
Beta of Strain	$\beta\varepsilon$	.076	.059	.054	.038	.030	.024

Using the reults from a proof test of a Kevlar-49 strand (gage length = 254 mm) at 70°C the number of individual fiber breaks can be determined.

$\beta\varepsilon = \beta_L / \varepsilon$

$\beta\varepsilon = 9.50 \times 10^3$ gms / 3.0×10^5 gms/ε

$\beta\varepsilon = 3.1 \times 10^{-2}$

Note : This result is somewere between $\delta = 10$ mm. and 50 mm. (Table VIII.) and correcting for gage length , equation (6), **δ = 50 mm.** .

The percent of fiber failures F as a function of a possible ineffective gage length is determined by equation (4).

$$F = 1 - \exp\{-(\beta_{\varepsilon GL} / \beta_{\varepsilon 70c})^{\alpha 1}\}$$

TABLE IX. PERCENT FIBER BREAKS AS A FUNCTION OF OF INEFFECTIVE GAGE LENGTH 70°C

δ	β_ε	F	#of fiber breaks (267 per bundle)
.1	.076	.0001	.03
.5	.059	.005	1
1.0	.054	.01	3
10.	.038	.1	27
50	.030	.39	104
100	.027	.63	168
254	.024	.99	267

Based on the fact that the strand was heated to 70°C it would not be unreasonable to expect that the ineffective length δ approaches 50 mm. Therefore from Table IX, 39 percent of the fibers broke.

3. GRAPHITE TESTING

The model was then examined for graphite fibers based on known test data from individual fiber testing conducted during this study. For gage length = 50 mm;

$$\beta_L = 15.5 \text{ gmf} \quad \alpha = 4.0 \quad \beta_\varepsilon = 1.72 \times 10^{-2} \text{mm/mm} \quad E = 900 \text{ gm}/\varepsilon$$

Using equation (6), β_L = 13.0gmf, for gage length = 100 mm. Now applying this information to a dry bundle consisting of 3000 fibers 254 mm. long the number of fiber failures can be predicted as a function of displacement using equation (4), (Table X.)

$$F = 1 - \exp\{ -(\varepsilon/\beta\varepsilon)^{\alpha\varepsilon} \}$$

$$\beta\varepsilon_{50mm} = .0145 \text{ mm/mm}$$

TABLE X. PERCENT FIBER BREAKS AS A FUNCTION OF STRAIN FOR GAGE LENGTH OF 254 MM.

ε	ΔL (mm)	F	No. of Fiber Failures
.001	.254	.00006	<1
.002	.508	.0009	3
.004	1.016	.015	44
.006	1.524	.07	214
.008	2.032	.21	626
.010	2.54	.46	1306
.012	3.04	.69	2083
.014	3.56	.89	2666
.016	4.06	.98	2929
.018	4.57	.99	2992
.020	5.08	.999	2999

For example, based on what is know of the successful Kevlar test at 70 ^oC (δ=50 mm) it is desired to break 40 percent of the fibers during preloading. So now, the graphite bundle would be loaded until delta length equals 2.5 mm. (Table X).

These results can be graphical confirmed by reviewing a representative load-displacement plot (Figure 18) of a dry bundle (gage length = 254 mm.).

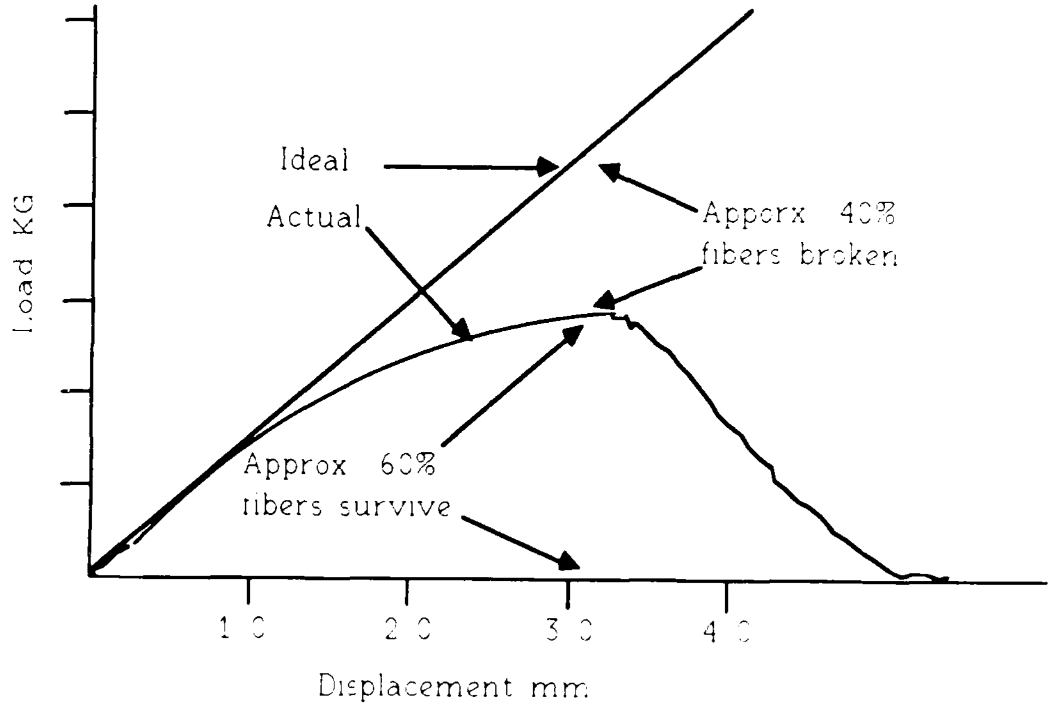

Figure 18 Load-Displacement Plot

APPENDIX D. TABULATED TEST RESULTS

TABLE XI. SINGLE GRAPHITE FIBER DIAMETER RESULTS (MICRONS)

008 SERIES		019 SERIES	
6.707	7.282	6.208	7.291
6.784	7.283	6.435	7.300
6.797	7.285	6.515	7.310
6.800	7.285	6.593	7.314
6.815	7.290	6.730	7.316
6.852	7.294	6.798	7.333
6.866	7.306	6.804	7.335
6.898	7.307	6.815	7.338
6.918	7.318	6.825	7.345
6.940	7.321	6.889	7.350
6.964	7.322	6.915	7.350
6.965	7.324	6.945	7.351
6.973	7.330	6.962	7.364
6.983	7.335	6.996	7.372
6.997	7.336	6.998	7.372
6.997	7.337	7.015	7.380
7.020	7.341	7.030	7.389
7.039	7.358	7.042	7.395
7.045	7.359	7.054	7.426
7.060	7.370	7.062	7.430
7.066	7.376	7.062	7.440
7.084	7.377	7.070	7.447
7.104	7.377	7.101	7.453
7.115	7.378	7.137	7.454
7.140	7.388	7.145	7.458
7.141	7.397	7.147	7.480
7.142	7.403	7.178	7.482
7.179	7.420	7.180	7.507
7.184	7.425	7.197	7.516
7.209	7.445	7.199	7.551
7.227	7.456	7.204	7.569

7.236	7.473	7.206	7.585
7.241	7.573	7.208	7.586
7.243	7.576	7.212	7.589
7.255	7.650	7.212	7.600
7.258	7.682	7.216	7.623
7.270	7.760	7.219	7.670
7.275	7.836	7.223	7.738
		7.227	7.792
		7.243	7.825
		7.289	7.871

TABLE XII. SINGLE GRAPHITE FIBER FAILURE LOAD RESULTS

019-N	019-I	008-N	008-I
8.096	4.303	10.592	8.022
9.284	5.015	10.654	9.255
9.734	6.819	10.776	9.653
10.219	7.368	11.451	10.707
10.342	8.111	11.483	11.018
10.772	9.899	12.043	11.157
11.686	10.324	12.123	11.243
12.505	10.636	12.141	11.622
12.690	11.751	12.252	11.781
12.768	11.770	12.398	11.804
13.180	12.440	12.439	12.499
13.196	12.448	12.664	12.623
13.457	12.667	12.858	13.071
13.762	12.904	13.604	13.157
13.872	13.703	14.440	13.297
13.980	13.705	14.614	13.630
14.271	14.265	15.107	14.140
14.528	14.502	15.209	14.812
14.678	14.528	15.241	14.914
14.767	14.811	15.372	14.936
15.033	15.565	15.567	16.116
15.521	16.957	15.851	16.369
15.522	17.073	16.270	16.633
15.615	17.726	16.272	16.941
15.956	17.804	16.664	17.560
16.145	18.259	17.352	17.607
16.242	18.801	17.360	17.923
16.369	18.956	18.009	18.992
17.545	19.392	18.064	20.603
18.081	19.556	18.586	20.911
19.962	19.610	19.544	21.572
20.352	19.915	20.490	25.442
20.627			

N = NPSIT Results I = INSTRON Results

TABLE XIII. FAILURE LOAD RESULTS OF SERIES 019 GRAPHITE

TRIAL (I)	LOAD (gms)	DIAMETER (microns)	TRIAL (N)	LOAD (gms)	DIAMETER (microns)
1	3.447	7.219	1	7.284	7.585
2	4.303	7.440	2	8.096	6.815
3	5.015	7.426	3	9.284	6.800
4	6.819	7.430	4	9.734	7.242
5	7.368	6.992	5	10.219	7.350
6	8.111	6.998	6	10.342	6.515
7	9.899	7.364	7	10.772	7.344
8	10.324	7.145	8	11.686	6.593
9	10.636	7.054	9	12.505	7.227
10	11.751	7.335	10	12.690	7.482
11	11.770	7.333	11	12.768	7.516
12	12.440	6.730	12	13.180	7.589
13	12.448	7.030	13	13.196	7.458
14	12.667	7.042	14	13.457	7.453
15	12.904	7.147	15	13.762	7.507
16	13.703	6.804	16	13.872	7.600
17	13.705	7.289	17	13.980	7.447
18	14.265	7.197	18	14.271	7.015
19	14.502	6.825	19	14.528	7.454
20	14.528	7.825	20	14.678	7.380
21	14.811	7.569	21	14.767	7.206
22	15.565	6.945	22	15.003	7.551
23	16.957	7.062	23	15.521	7.137
24	17.073	7.310	24	15.522	6.889
25	17.726	7.291	25	15.615	7.350
26	17.804	7.316	26	15.596	7.623
27	18.259	7.738	27	16.145	7.101
28	18.801	7.351	28	16.242	7.208
29	18.956	7.372	29	16.369	7.872
30	19.392	7.199	30	17.545	7.212
31	19.556	7.216	31	18.081	7.338
32	19.610	7.070	32	19.962	7.389
33	19.915	6.962	33	20.352	7.586
			34	20.627	7.792

TABLE XIV. FAILURE LOAD RESULTS OF SERIES 008 GRAPHITE

TRIAL (I)	LOAD (gms)	DIAMETER (microns)	TRIAL (N)	LOAD (gms)	DIAMETER (microns)
1	5.504	7.283	1	10.234	6.832
2	8.022	7.388	2	10.592	7.336
3	9.255	6.852	3	10.654	6.707
4	9.356	6.815	4	10.776	7.403
5	9.653	6.965	5	11.451	6.964
6	10.707	7.241	6	11.483	7.445
7	11.018	6.918	7	12.043	7.236
8	11.157	7.066	8	12.123	7.140
9	11.243	7.285	9	12.141	7.039
10	11.622	7.084	10	12.252	7.321
11	11.781	7.060	11	12.398	7.282
12	11.804	7.330	12	12.439	7.318
13	12.499	7.377	13	12.664	7.141
14	12.623	7.576	14	12.858	7.307
15	13.071	7.358	15	13.604	7.337
16	13.157	7.306	16	14.440	7.322
17	13.297	7.285	17	14.614	7.275
18	13.630	7.258	18	15.107	6.784
19	14.140	7.224	19	15.209	7.294
20	14.812	7.184	20	15.241	7.378
21	14.914	7.045	21	15.372	7.115
22	14.963	7.142	22	15.567	7.376
23	16.116	6.973	23	15.851	7.270
24	16.369	7.020	24	16.270	7.425
25	16.633	6.944	25	16.272	7.179
26	16.941	7.456	26	16.664	7.377
27	17.560	7.397	27	17.352	7.359
28	17.607	7.473	28	17.360	7.209
29	17.923	7.335	29	17.360	7.243
30	18.992	7.420	30	18.009	7.836
31	20.603	6.997	31	18.064	6.997
32	20.911	7.682	32	18.586	7.324
33	21.572	7.642	33	19.544	6.800
34	25.442	7.760	34	20.490	6.983

TABLE XV. COMPOSITE STRAND FAILURE LOAD RESULTS

PRELOADED (KG)		NON-PRELOADED * (KG)	
43.17	46.76	40.80	47.29
43.38	46.79	42.18	47.54
43.41	46.95	42.38	47.69
43.81	47.28	43.37	48.05
44.40	47.46	44.48	48.31
44.75	47.84	44.86	48.44
44.94	47.97	44.89	49.08
45.69	49.02	45.18	50.35
45.72	49.91	45.61	50.60
45.74	49.99	46.53	50.80
46.04	50.17	46.79	51.91
46.42		47.15	52.22

* Preliminary data on AS4-Graphite Strand Intrinsic Strength.
By: E.M. Wu, N.Q. Nguyen and G.W. Nypiuk, Lawrence Livermore National Labratory, Livermore, California, April, 1972

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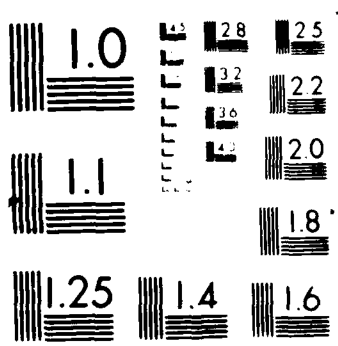
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